

SEEING AND VISUALIZING: IT'S NOT WHAT YOU THINK

An Essay On Vision and Visual Imagination*

ZENON PYLYSHYN, RUTGERS CENTER FOR COGNITIVE SCIENCE

Table of Contents

Preface	v
1. The Puzzle of Seeing	1-1
1.1 Why do things look the way they do?.....	1-1
1.2 What is seeing?	1-2
1.3 Does vision create a "picture" in the head?	1-3
1.3.1 <i>The richness of visual appearances and the poverty of visual information</i>	1-3
1.3.2 <i>Some reasons for thinking there may be an inner display</i>	1-6
1.4 Some problems with the Inner Display Assumption: Part I: What's in the display?.....	1-10
1.4.1 <i>How is the master image built up from glances?</i>	1-10
1.4.2 <i>What is the form of non-retinal information?</i>	1-11
1.4.3 <i>How "pictorial" is information in the "visual buffer"?</i>	1-17
Some further problems with the Inner Display Assumption Part II: <i>seeing or figuring out?</i>	1-22
1.4.4 <i>A note about terminology</i>	1-23
1.4.5 <i>"Seeing X" versus "believing that what you saw is X"</i>	1-24
1.4.6 <i>Reports of what something "looks like": What do they mean?</i>	1-25
1.4.7 <i>Vision and conscious appearance: Can they be separated?</i>	1-27
1.5 Where do we go from here?.....	1-28
2. The Independence of Vision and Cognition	2-1
2.1 Is Vision distinct from reasoning?.....	2-1
2.1.1 <i>What determines what we see? Do we see what we expect to see?</i>	2-1
2.2 The case for the continuity of vision and cognition	2-2
2.2.1 <i>The "New Look" in the psychology of perception</i>	2-2
2.2.2 <i>The perspective of neuroscience</i>	2-4
2.2.3 <i>The perspective of robot vision</i>	2-5
2.2.4 <i>Seeing and knowing: Where do we stand?</i>	2-8
2.3 Some reasons for questioning the continuity thesis.....	2-9
2.3.1 <i>Evidence of the cognitive impenetrability of illusions</i>	2-9
2.3.2 <i>Evidence of the independence of principles of visual organization and of inference</i>	2-10
2.3.3 <i>Neuroscience evidence for top-down attenuation and gating of visual signals</i>	2-11
2.3.4 <i>Evidence of dissociation of visual and cognitive functions in the brain</i>	2-12
2.3.5 <i>Evidence that cognitive penetration occurs in pre-perceptual and post-perceptual stages</i>	2-13
2.4 Distinguishing perceptual and decision stages: Some methodological issues	2-14
2.5 Some examples in which knowledge is claimed to affect perception	2-15
2.5.1 <i>"Intelligent" interpretations of inherently ambiguous information</i>	2-15
2.5.2 <i>Experience and "hints" in perceiving ambiguous figures and stereograms</i>	2-15
2.5.3 <i>Learning to "see" differently: A case of controlling focal attention?</i>	2-18
2.5.3.1 <i>Cultural and linguistic effects on perception</i>	2-19
2.5.3.2 <i>The case of "expert" perceivers</i>	2-19
2.5.3.3 <i>Attention and perceptual learning</i>	2-21

* Manuscript of a forthcoming book from MIT Press. Please do not quote without permission. © 1998 by Zenon Pylyshyn

2.5.4	<i>Focal attention as an interface between vision and cognition</i>	2-22
2.6	Conclusions: Early vision as a cognitively impenetrable system.....	2-22
3.	The Architecture of the Early Vision System: Components and Functions	3-1
3.1	Some intrinsic architectural factors determining the visual percept.....	3-1
3.1.1	<i>Natural Constraints in Vision</i>	3-1
3.1.1.1	An example of the use of natural constraints in feature labeling.....	3-4
3.1.1.2	Other constraints: The “rules” of visual analysis.....	3-9
3.1.2	<i>On “Intelligence” and “Problem-solving” in vision</i>	3-13
3.1.3	<i>Constraints do not reflect high-frequency or physically permissible real-world principles</i> ...	3-17
3.2	What is computed by the encapsulated early vision system?.....	3-19
3.2.1	<i>What are the inputs to the visual system?</i>	3-20
3.2.1.1	Cross-modal visual processing.....	3-21
3.2.1.2	Synesthesia: Cross-Modal perception?.....	3-21
3.2.1.3	Should “visual input” include actual and potential motor actions?.....	3-23
3.2.2	<i>What are the outputs of the visual system?</i>	3-25
3.2.2.1	The visual output: Categories and surface layouts.....	3-25
3.3	Some subprocesses of the visual system.....	3-30
3.3.1	<i>Stages in early vision: Microgenesis of vision</i>	3-33
3.4	Visual control of action: An encapsulated system?.....	3-35
3.4.1	<i>Evidence from studies of eye movements and reaching</i>	3-36
3.4.2	<i>Evidence from clinical neurology</i>	3-37
3.4.3	<i>Evidence from animal studies</i>	3-37
3.5	Is “vision” one system or many?.....	3-38
4.	Focal Attention: How cognition Influences Vision	4-1
4.1	Focal attention in visual perception.....	4-1
4.2	Focal attention as selective filtering.....	4-2
4.3	Allocation of visual attention.....	4-4
4.4	Individuation: A precursor to attentional allocation?.....	4-8
4.4.1	<i>Individuation is different from discrimination</i>	4-8
4.4.2	<i>Individuating an object is distinct from encoding its location or visual properties</i>	4-10
4.5	Visual attention is directed at <i>Objects</i>	4-12
4.5.1	<i>The capacity of the “visual buffer”</i>	4-13
4.5.2	<i>Extracting visual information from within and between objects</i>	4-13
4.5.3	<i>Endurance of object-based attention despite changes in the object’s location</i>	4-16
4.5.4	<i>Endurance of object-based attention despite temporal interruption</i>	4-18
4.5.5	<i>Object-based attention when “object” is not defined spatially</i>	4-19
4.6	Neural bases and neuropsychological evidence for object-based information access.....	4-20
4.6.1	<i>How do the ventral and dorsal visual systems coordinate information?</i>	4-20
4.6.2	<i>Visual Neglect</i>	4-21
4.6.3	<i>Balint Syndrome</i>	4-22
4.7	What is selected in visual attention?.....	4-23
5.	The Link Between Vision and the World: Visual Indexes	5-1
5.1	Individuating primitive visual objects: Visual Index (<i>FINST</i>) Theory.....	5-1
5.2	Empirical Support for Visual Index Theory.....	5-10
5.2.1	<i>The multiple object tracking (MOT) task</i>	5-10
5.2.2	<i>Other properties of visual indexing revealed through MOT</i>	5-13
5.2.3	<i>Selecting objects in a search task</i>	5-15
5.2.4	<i>Inhibition of return</i>	5-18
5.2.5	<i>Subitizing</i>	5-18
5.3	Why do we need a special connection between vision and the world?.....	5-21
5.3.1	<i>Essential demonstratives</i>	5-24
5.3.2	<i>Situated vision for robots</i>	5-27
5.4	Indexes and the development of the object concept in infants.....	5-30

5.5	How can mental particulars be bound to things in the world? Possible Implementations of the FINST indexing mechanism.....	5-35
	Appendix 5A: Sketch of a partial network-implementation of the FINST Indexing mechanism	5-38
6.	Seeing With the <i>Mind's Eye 1: The Puzzle of Mental Imagery</i>.....	6-1
6.1	What is the puzzle about mental imagery?	6-1
6.2	Content, form and substance of representations	6-5
6.3	What is responsible for the pattern of results obtained in imagery studies?	6-6
6.3.1	<i>Cognitive architecture or tacit knowledge</i>	6-6
6.3.2	<i>Problem-solving by "mental simulation": Some additional examples</i>	6-10
6.3.2.1	Scanning mental images.....	6-11
6.3.2.2	The "size" of mental images.....	6-14
6.3.2.3	Mental "paper folding".....	6-15
6.3.2.4	Mental Rotation.....	6-17
6.3.3	<i>A Note concerning tacit knowledge and the criterion of cognitive penetrability</i>	6-18
6.3.4	<i>Summary of some possible reasons for observed patterns of imagery findings</i>	6-20
6.4	Some alleged properties of images.....	6-21
6.4.1	<i>Depiction and mandatory properties of representations</i>	6-21
6.5	Mental imagery and visual perception.....	6-24
6.5.1	<i>Interference between imaging and visual perception</i>	6-25
6.5.2	<i>Visual illusions induced by superimposing mental images</i>	6-26
6.5.3	<i>Imagined versus perceived motion</i>	6-28
6.5.4	<i>Extracting novel information from images: Visual (re)perception or inference?</i>	6-29
6.5.5	<i>What about the experience of "visualizing"?</i>	6-32
7.	Seeing With the <i>Mind's Eye 2: Searching for a Spatial Display in the Brain</i>.....	7-1
7.1	Real and "functional" space.....	7-1
7.2	Why do we think that images are <i>spatial</i> ?	7-5
7.2.1	<i>Physical properties of mental states: crossing levels of explanation</i>	7-5
7.2.2	<i>Inheritance of spatial properties of images from perceived space</i>	7-8
7.2.2.1	Scanning when no surface is visible	7-10
7.3	The exploitation of proprioceptive or motor space	7-13
7.3.1	<i>Visuomotor interaction with images</i>	7-16
7.4	The search for a real spatial display.....	7-17
7.4.1	<i>Preface: Does biological evidence have a privileged status in this argument?</i>	7-17
7.4.2	<i>The search for a display in the brain</i>	7-18
7.4.2.1	The argument from clinical cases of brain damage.....	7-22
7.4.3	<i>What would it mean if all the neurophysiological claims turned out to be true?</i>	7-24
7.4.4	<i>Mental Imagery and the visual system: Is the 'mind's eye' just like a real eye?</i>	7-27
7.4.5	<i>What has the neuroscience evidence done for the "imagery debate"?</i>	7-28
7.5	What, if anything, is special about mental imagery?	7-29
7.5.1	<i>What I am not claiming: Some misconceptions about what is being objected to</i>	7-29
7.5.2	<i>What are some constraints that should be met by a theory of mental imagery?</i>	7-32
8.	Seeing With the <i>Mind's Eye 3: Visual Thinking</i>.....	8-1
8.1	Different "styles" of thinking.....	8-1
8.2	The form and content of thoughts: what we think with and what we think about.....	8-1
8.2.1	<i>The illusion that we experience the form of our thoughts</i>	8-1
8.2.2	<i>Do we think in words?</i>	8-2
8.2.3	<i>Do we think in pictures?</i>	8-3
8.2.4	<i>What form must thoughts have?</i>	8-6
8.3	How can visual displays help us to reason?.....	8-7
8.3.1	<i>Diagrams as logical systems that exploit visual operations</i>	8-7
8.3.2	<i>Diagrams as guides for derivational milestones (lemmas)</i>	8-9
8.3.3	<i>Diagrams as a way of exploiting visual generation</i>	8-11
8.3.3.1	Representing universal properties in diagrams.....	8-11

8.3.3.2	How vision generalizes.....	8-12
8.3.4	<i>Diagrams as ways of tracking instances and alternatives.....</i>	8-14
8.3.5	<i>Diagrams as spatial models and spatial memory.....</i>	8-15
8.3.6	<i>Diagrams as a way of deploying visual operations in place of logical inferences.....</i>	8-16
8.4	Thinking with <i>mental diagrams</i>	8-17
8.4.1	<i>Using mental images.....</i>	8-17
8.4.2	<i>Using mental models.....</i>	8-18
8.4.3	<i>What happens during visualization?</i>	8-19
8.5	Imagery and imagination.....	8-20
8.5.1	<i>How does creativity connect with imagery?</i>	8-22
8.5.1.1	Enhancing creative thinking.....	8-24
References		8-1

SEEING AND VISUALIZING: IT'S NOT WHAT YOU THINK

An Essay On Vision and Visual Imagination^{*}

ZENON PYLYSHYN, RUTGERS CENTER FOR COGNITIVE SCIENCE

PREFACE

This book is about how we see and visualize. But it is equally about how we are easily misled by our subjective experiences of these faculties. Galileo is said to have proclaimed (Galilei, 1610/1983; quoted in Slezak, submitted), "... if men had been born blind, philosophy would be more perfect, because it would lack many false assumptions that have been taken from the sense of sight." Many deep puzzles arise when we try to understand the nature of visual perception, visual imagery or visual thinking. As we try to formulate scientific questions about these human capacities we immediately find ourselves being misled by the *view from within*. Such traps are nothing new; psychology is used to being misled in this way. Since people first began to think about the nature of thinking, seeing and imagining, they have had to contend with the fact that the way these achievements appear to us on the inside does us little good, and indeed often lead us in entirely the wrong direction, when we seek a scientific explanation. Of course we have the option of putting aside the quest for a scientific explanation and set our goal towards finding a satisfying description in terms that are consonant with how seeing and imagining appear to us. This might be called a phenomenological approach to understanding the workings of the mind or the everyday folk understanding of vision.

There is nothing wrong with such a pursuit. Much popular psychology revels in it, as do a number of different schools of philosophical inquiry (e.g., ordinary language philosophy, phenomenological philosophy). Yet in the long term few of us would be satisfied with an analysis or a natural history of phenomenological regularities. One reason is that characterizing the systematic properties of how things seem to us does not allow us to connect with the natural sciences, to approach the goal of unifying psychology with biology, chemistry and physics. It does not help us to answer the *how* and *why* questions; How does vision work? Or, Why do things look the way they do? Or, What happens when we think visually?

The problem with trying to understand vision and visual imagery is that on the one hand these phenomena are intimately familiar to us from the inside so it is difficult to objectify them, and on the other hand the processes involved are also too fast and too ephemeral to be observed introspectively. The question, How do we see appears very nearly nonsensical: Why, we see by just looking, and the reason that things look as they do to us is that this is the way that they actually are. It is only by objectifying the phenomena, by "making them strange" that we can turn the question into puzzle that can be studied scientifically. One good way to turn the mysteries of vision and imagery into a puzzle that can be studied is to ask what it would take for a computer to see or imagine. But this is not the only way and indeed this way is often itself laden with our preconceptions, as I will try to show throughout this book.

The title of this book is meant to be ambiguous. It means both that seeing and visualizing are different from thinking (and from each other), and that our intuitive views about seeing and visualizing are largely born of a grand illusion. The message of this book is that seeing is different from thinking and to see is not,

^{*} Manuscript of a forthcoming book from MIT Press. Please do not quote without permission. © 1998 by Zenon Pylyshyn

as it often seems to us, to create an inner replica of the world we are observing or thinking about or visualizing. But, I'm afraid this is a long and not always an intuitively compelling story. In fact, its counterintuitive nature is one reason it may be worth telling. When things seem clearly a certain way it is often because we are subject to a general shared illusion. To stand outside this illusion requires a certain act of will and an determined look at the evidence. Few people are equipped to do this, and I am not deluded enough to believe that I am the only one who can. But some things about vision and mental imagery are by now clear enough that only deeply ingrained prejudices keep them from being the received view. It is to these that I address myself. If any of the claims appear radical it is not because they represent a leap into the dark caverns of speculative idealism, but only that some ways of looking at the world are just too comfortable and too hard to dismiss. Consequently what might be a straightforward story about how we see, becomes a long journey into the data and theory developed over the past 30 years.

The journey begins with the question of why things we see appear to us as they do. In chapter 1 I describe experiments and demonstrations, as well as providing general arguments, to try to persuade you that when you look around, the impression you have that you are creating a large panoramic picture in your head is a total illusion. When you *see*, there is no intermediate *picture* of the world anywhere, your subjective impression notwithstanding; there is just the world and your interpretation of the incoming information (and there is also a way to keep the two in correspondence, which is the topic of chapters 4 and 5). There is, however, a representation of the visual world; and here the great J. J. Gibson was wrong in trying to develop a theory of direct perception, unmediated by representations and reasoning. But there is no pictorial object, no spatially distributed, topographically organized, representation that we would call a picture, at least not by the time the visual information becomes available to our cognitive mind.

Chapter 2 goes on to make the argument that while the visual system is smart – honed by many millennia of evolutionary shaping – it is nonetheless essentially ignorant. The visual system (or at least the part of it that we will focus on, the so-called *early vision* system) does what it was designed to do with neither help nor hindrance from the cognizing mind. How it can do as well as it does in the face of the inherent uncertainty presented by the incoming visual data is one of the questions that has been explored most successfully in recent decades; it is one of the outstanding achievements of contemporary cognitive science. According to the thesis developed in Chapters 2 and 3, there are two primary ways in which the mind (or, as we will say, the cognitive system) affects visual processing. One is that it is able to control where it concentrates its efforts. It does this by determining where to look and, sometimes independent of that, where to focus attention. The second way is by considering the product of visual processing, together with everything else the whole organism knows and believes, in order to figure out what is actually in the visual scene. Chapter 3 continues this discussion and goes on to describe some of the recent findings from neuroscience and psychophysics concerning the nature of this largely automatic early vision system.

Chapters 4 and 5 take a second look at the idea introduced in these last two chapters – i.e., that focal attention plays an important role in connecting vision and cognition – and suggests that there must be a mechanism, closely related to attention, that also plays a crucial role in connecting visual representations with things in the world. This very special connection, which we refer to as visual indexing, allows parts of visual representations to be bound to parts of the visual world so that they can refer to these parts directly, rather than in a way that is mediated by an encoding of the properties that these things have. Visual indexes serve very much like what are called demonstrative references, the sort of reference that we might make in language when we refer to *this* or to *that* without regard to what the *this* and the *that* are or what properties they may have. We *pick out* and individuate primitive visual objects as a precursor to focusing attention on them and encoding their properties. Such visual indexes play an important role in attaching symbols to things and they also play a role in allowing visual images to inherit spatial properties of perceived space. The ideas introduced in chapter 5 serve an important function in filling in some of the missing aspects of the sort of symbolic representations of percepts introduced in chapter 1 and also in explaining some of the alleged spatial properties of mental images discussed in subsequent chapters.

Finally the last three chapters build on the ideas introduced in chapters 1 through 5 to attempt to make sense of some of the puzzling aspects of mental imagery. The message in these last chapters is that, notwithstanding what it feels like to visualize or to examine a mental image in one's mind's eye, imagining

and visualizing are a form of reasoning. And, as with all forms of reasoning, we have very little conscious access to the real machinery of the mind; the machinery that encodes our thoughts and that transforms them as we reason, as we draw inferences, as we search our memory, and as we understand the evidence of our senses – including that which arrives in the form of language. Because our intuitions and our introspections are either silent or are seriously misleading concerning what our thoughts are like and how they are processed, we need to impose some constraints on our speculations on the subject. In the last three chapters, and especially in Chapter 8, I consider these constraints and, drawing on work by Jerry Fodor (Fodor, 1975) as well as our joint work (Fodor & Pylyshyn, 1988). I argue that any form of reasoning, including reasoning by visualizing, must meet the constraints of productivity and systematicity. This leads to the inevitable conclusion that reasoning with mental imagery or reasoning by visualizing or “visual thinking” requires a combinatorial system – a Language of Thought – that itself is not in any sense “pictorial”. While this conclusion may appear to fly in the face of an enormous amount of evidence collected over the past thirty years showing that thinking using mental images is more like seeing pictures than it is like reasoning with an “inner dialogue”, I argue in detail in chapters 6, 7 and 8, that the evidence does not support the assumption that visualizing is special in the way that current theorists have assumed it to be. The data, I will argue, have been widely and seriously misunderstood.

Even if the reader agrees with the general thrust of this discussion, there will no doubt remain many areas of legitimate discomfort. Some of this discomfort concerns the apparent discrepancy between what it feels like to see and to visualize and the class of symbolic computational theories that have been developed in cognitive science. This discrepancy is addressed in various places in the book, but in the end it cannot be dismissed, simply because of our deep-seated commitment to what Dan Dennett has called the “Cartesian Theater” view of the mind, a view that is deeply embedded in our psyche. This “explanatory gap” was around long before cognitive science and the computational view of mind (in fact it was the subject of considerable debate between Nicolas Malebranche and Antoine Arnauld in the seventeenth century, see Slezak, submitted). In addition to this deeply held world view, there are also other aspects of mental imagery where the discomfort owes more to the way we conceive of certain problems than it does to how the contents of our conscious experience strike us. I consider one class of these in Chapter 8: They include the close connection that may exist between imagery, imagination and creativity. I will argue that this connection, while real enough, does not favor one view of the nature of mental imagery over another. It rests, rather, on our ignorance of the nature of creativity and on the puzzle of where new thoughts or new ideas come from.

Although the book devotes considerable space to the salubrious task of clarifying many misconceptions that pervade the study of vision and visualization, the principal goal is to provide a new analysis of the nature of visual processing and of mental imagery. The analysis rests on both empirical evidence, some of which comes from the author’s laboratory, and on a reinterpretation of well-known findings. This book is in many ways a continuation of the investigation of cognition that began with my *Computation and Cognition* (Pylyshyn, 1984a), but it focuses on problems within one of the most highly developed areas in cognitive science, visual perception, and traces the relation between the study of vision, and the study of mental imagery, and the study of thinking more generally.

SEEING AND VISUALIZING: IT'S NOT WHAT YOU THINK

An Essay On Vision and visual Imagination

ZENON PYLYSHYN, RUTGERS CENTER FOR COGNITIVE SCIENCE

1. THE PUZZLE OF SEEING

1.1 Why do things look the way they do?

Why do things appear to us as they do? We don't even have a clear idea of what kind of story should count as an answer. The whole notion of "appearing" seems problematic. On one hand it is obvious that things appear to us the way they do because, barring illusions, *that's the way they are!* On the other hand, it is also clear that a particular thing being the way it is, is neither necessary nor sufficient for our *seeing* it the way we do. We know that things can look quite different to us in different circumstances and perhaps they do look different to others. So it is not unreasonable for us to ask what is responsible for our seeing things as we do, as opposed to seeing them in some other way.

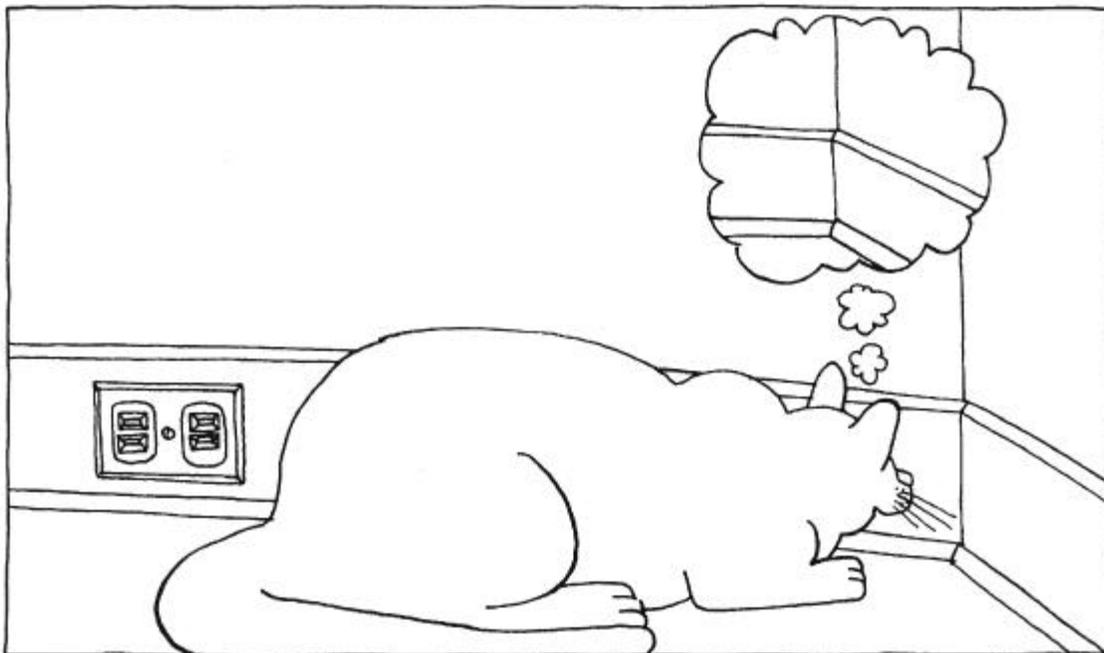
Despite the dramatic progress that has been made in the study of visual perception in the past half century, the question of why we see things the way we do in large measure still eludes us. The question of what and how and why we see are daunting. Surely the pattern of light arriving at our eyes is responsible for our visual perception. Must this be so – is light both necessary and sufficient for perception? Could we not also "see" if our eye or our brain was electrically stimulated in the right way? And what of the experience of seeing: Is that constitutive of vision; is that what visual perception *is*? Would it make any sense to ask what is the product or even the purpose of visual perception? Could there be full-blooded visual perception in the absence of any awareness of something being seen; without a visual experience? The mystery of the experience of seeing is deep and is at the heart of our understanding (or failure to understand) the nature of consciousness itself. Is it possible to have a scientific understanding of vision without first understanding the mystery of consciousness? The scientific world thinks it is and it has already made a great deal of progress in doing so. But is this because it has presupposed a view of what it is to see – a set of tacit assumptions about such things as the relation between our experience of seeing and the nature of the information processing performed by the visual system?

I do not intend this book to be about consciousness, or even about our conscious visual experience, because I believe there is little that science can say about this notion at the present time. That's not to say that it is not of the greatest importance and perhaps even central to understanding human nature. It is also not to say that there is nothing worthwhile to be said on the topic of consciousness, because consciousness has become a very active topic of scholarship and a great deal is being said, much of it quite fascinating. Nonetheless, most of what is being said is by way of preliminary scene-setting and conceptual clarification. It's about such surprising empirical findings as those showing that certain functions can be carried out without conscious awareness. A lot of the discussion is also about what consciousness is not. It's about such things as why a theory that says consciousness *is* such and such a brain property (a certain frequency of brain waves, activity a certain location in the cortex) or a particular functional property (such as the contents of short-term working memory, or the mind's observation of its own functioning) simply misses the point. The only part of this discussion that will concern us will be the way in which the content of our experience when we see, visualize and think misleads us and contaminates many of our scientific theories of

vision and of related processes such as visualizing and imagining. For this reason we devote much of the present chapter to a discussion of what the visual provides to the mind. The closely related question of how the cognizing mind affects visual perception is raised in Chapter 2 and some of that discussion takes us back to the troublesome notion of the nature of visual experience.

1.2 What is seeing?

One reason why understanding vision is so difficult is that we who are attempting to understand the process are so deeply embedded in the phenomenology of perception: We know what it *feels* like to see. We look out and see the world and we cannot escape the impression that what we have in our heads is a detailed, stable, extended and veridical display that corresponds to the scene before us. Of course most of us have also seen enough examples of so-called “optical illusions” so that we are prepared to admit that what we see is not always what is truly the case. Yet at the same time we have much more difficulty shedding the view that in our heads is a display that our inner first-person self, or our cognitive homunculus, observes. There are other phenomena relating to our experience of seeing a “picture in our head” that are even more problematic. These include the similar experience that we have without any visual input: the experience that accompanies mental imagery or visual thinking. The more we analyze what must be going on, and the more we examine the empirical evidence, the more puzzling the process becomes and the less tenable our intuitions. Indeed we find that not only must we dispense with the “picture in the head”, but we must revise our ideas concerning the nature of the mechanisms involved in vision and concerning the nature of the internal informational states corresponding to percepts or images. What can never serve as a theory of vision is a theory that says that vision creates a copy of the world inside the head, as the Kliban cartoon in Figure 1-1 suggest is the case with a cat. The understanding that this sort of theory will not do is what makes this cartoon funny. Yet it is non-trivial to say what exactly is wrong with a theory that even remotely resembles this sort of story. This I will attempt in the present book, mostly in this chapter and in Chapters 6 and 7.



*Figure 1-1. A theory of vision such as this is a non-starter, even for a cat!
B. Kliban (American, 1935-1990). From the book Cat, by B. Kliban. Use by permission only. All rights reserved. © Judith K. Kliban.*

In what follows I will examine some of these counter-intuitive aspects of the process of visual perception and mental imagery. For now the following examples will suffice to warn us that our intuitions are a notoriously bad source of ideas as to how the visual system works. The message of these examples is that we should not be surprised to find that our scientific theories will look quite different from the way we might imagine them if we were trying to be faithful to how vision seems to us from the inside – to the phenomenology of visual perception.

1.3 Does vision create a “picture” in the head?

1.3.1 The richness of visual appearances and the poverty of visual information

Let’s call our conscious experience of how things seem to us when we look at them, the “phenomenal” content of our perception. As we look around, the phenomenal content of our perception is that of a detailed and relatively stable panorama of objects and shapes laid out in three-dimensions. Even without turning around we experience a broad expanse (about 180 degrees of panorama), full of details of the scene; its colors and textures, its shapes and boundaries and the meaningful things that populate our visual scene – the familiar objects and people that we instantly recognize. Even if there was little or nothing in the scene that we recognized as familiar, say if we had just landed on the surface of Mars, we would still have no trouble seeing shapes and surfaces. We would see a variety of individual objects, set against some background that remained perceptually secondary (i.e., we would experience what Gestalt psychologists called a “figure-ground” separation). We would see each of these objects as having a certain shape consisting of parts arranged in some spatial relation to one another. We would see some of the objects as further away and some as closer, with the closer objects partially occluding our view of the further objects. We would see that the partly-occluded objects continued behind the closer ones; we would *not* see the occluded objects as partial objects or as having the shape of the visible fragment – though it is physically possible that this could in fact be their shape. The phenomenal content of our perception would continue to be that of a world of three-dimensional objects even though most of every object would be hidden from our view, either by other objects or by the front of the object itself. If we could turn freely to inspect the scene around us there would be no sharp discontinuity between the part of the scene currently on our retina and the entire 360 degrees of the layout (e.g., we could accurately point to objects behind us, as Attneave & Farrar, 1977, showed).

This phenomenal experience is, as far as we know, universal to our species and probably innate. We don’t give it a second thought because it seems to us that what we are seeing is what there is to see. But even a cursory examination makes it abundantly clear that much more is going on than we might assume (one might be tempted to say that there is more to vision than meets the eye). Consider what the brain has to work with in achieving this familiar experience. The light-sensitive surfaces of the eye (the retinas) are two-dimensional, so the sense of depth must come from some other source of information. We know that at least part of it comes from the difference between the patterns that the two eyes receive, but why (and how) does this produce the experience of seeing a three-dimensional world? No matter how well we understand the mechanism of stereo perception (and it is one of the most studied problems in visual science) we are very far from breaking through the mystery of this question. The story gets even murkier as we further examine the information that the brain receives from the eyes. The retinas themselves are not uniform. Only a small central region (the fovea), about the size of the area covered by your thumb held at arm’s length, has sufficient acuity to recognize printed characters at the normal reading distance. Outside of that region our visual acuity drops off rapidly and by the time we get to where the edge of a movie screen would normally fall in our field of vision, the acuity is so poor that if that were how we saw the world generally we would be considered legally blind. As we move off from the central fovea the eye also becomes color blind, so almost all color information comes from the tiny area of the fovea (and what color reception there is varies in its degree of responsiveness to the yellow-green dimension depending on how far out from the fovea it is). Moreover our eye’s focal length differs considerably for red and blue colors so one end of the spectrum is invariably out of focus by about the degree of magnification of off-the-shelf reading glasses. There is also a region of the retina, considerably larger than the fovea and lying about 10 to

13 degrees away, where the retinal nerve fibers come together forming a cable to the brain. This region has no receptors: it is our blind spot. It is easy to show that no information is registered at the location of the blind spot (look at figures below), yet we are unaware of the blind spot: It does not interfere with our phenomenal experience of a uniform perceptual world. Even when the spot is located over an elaborate pattern, we do not see a hole in the pattern. In fact we even see objects move through the blind spot without discontinuity, and we can locate the moving object precisely as being inside the blind spot at the appropriate time (Cai & Cavanagh, 2002). This phenomenon, which many people refer to as “filling in” provides some important clues as to how vision works and how vision, *as an information-processing system*, relates to our phenomenal experience of seeing. We will return to this most perplexing question later.

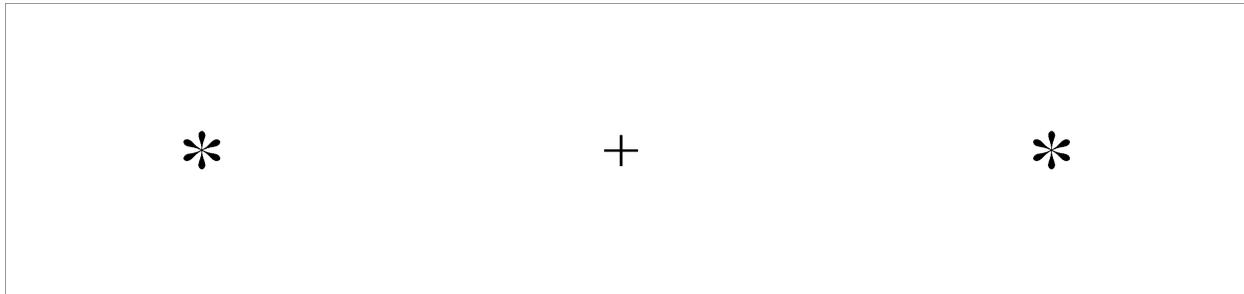


Figure 1-2: If you close your right eye and stare at the plus sign with your left eye at a distance of about 10 to 12 inches from the paper (varying the distance as you experiment) you will find that the asterisk on the left disappears from view at some appropriate distance. If you repeat this with your right eye the asterisk on the right will disappear. This is because they fall on the blind spot of each eye. Now repeat the experiment on the figure below.

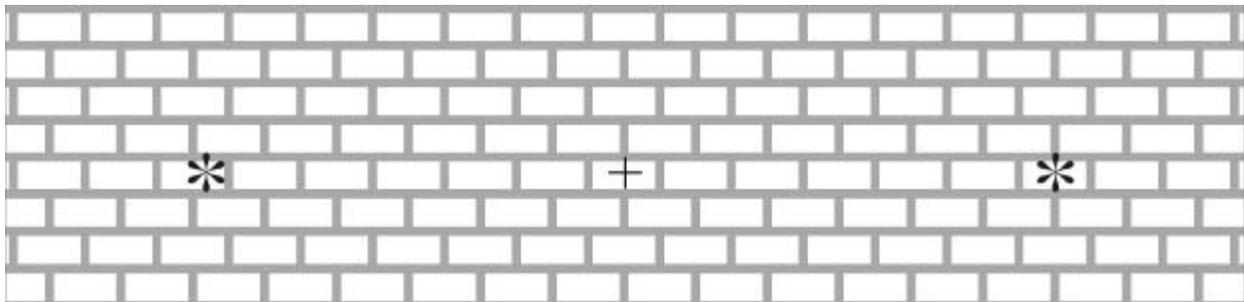


Figure 1-3: If you repeat the above experiment on this figure, held at the same distance where the asterisk disappeared on the previous figure, you may find that the bricklike pattern, though somewhat indistinct, remains visible without a gap. This is a case of what has been called “filling in”. But is there some place in your mind/brain where there is an inner display that has filled in the missing pattern?

The properties of the retina (including its blind spot and other ways in which it distorts the incoming information because it is not flat and the distribution of rods and cones is not uniform) already provides

some reason to be concerned about how the brain gets to have such a large expanse of visual experience¹. But it gets much worse. For the eyes are in constant motion, jumping around in rapid saccades several times in each second and generally spending only a fraction of a second gazing in any one direction. The retina, our primary contact with the visual world, is being continually smeared with moving information (moving so rapidly that the nervous system cannot assimilate any detailed information during the rapid saccade, which can take as little as 3 one-hundredths of a second to sweep its path). And yet the world does not appear to move or flicker, and indeed we are typically unaware of the saccades. How do we see a rich and stable visual panorama in the face of such dynamic and impoverished information?

The intuitive answer that almost universally leaps to mind is that although the *retina* may get a degraded, nonuniform, rapidly-changing peephole-view of the world, you, the one who does the seeing, do not receive such impoverished information. What you see is a uniformly detailed, gapless, panoramic and stable view – rather like a three-dimensional picture – of the world built up from the sketchy unstable inputs from the two eyes. This is the first-person view, the world that your “self” (the subject in your claim that “I see”) gets to examine and enjoy. It is impossible for us to view what happens in our own perception in any other way. I think: *My eyes* may be moving and they may have poor resolution with a blind spot and all that, but *I, the person observing these events, do not have any of these problems*. What I see is a 3D layout of surfaces and objects that have colors and shapes and the entire scene stands still and covers a wide panorama (180 or more degrees). Consequently, so the argument goes, there must be something that has these properties (of breadth, depth and stability), and where else could it be but in the head? Enter what Dan Dennett picturesquely calls the *Cartesian Theater*, after René Descartes who, by implication (though not explicitly), proposed such an inner image or screen onto which the eye projects its moving peephole view and paints the larger picture.

But, tempting as it is, the Cartesian Theater creates far more problems than it solves. (Dennett, 1991) discusses a number of difficulties raised by this “inner eye” idea and shows that it leads to one conceptual impasse after another. The whole idea of an inner screen rests on a well-known fallacy, called the “intentional fallacy” in philosophy and sometimes the “stimulus error” in the structuralist psychology of Wundt and Titchener (or, in the case of Wundt and Titchener, the stimulus error meant attributing to one’s introspective experience, the properties one knows the objective stimulus to possess). The temptation to make the mistake of attributing to a mental representation the properties of what it represents is very difficult to avoid. This issue arises in an extreme form in discussions of mental imagery where the temptation appears to be very nearly inescapable – I will return to it in Chapters 6-8 (for an extensive discussion of this point, see Pylyshyn, 2002). What I propose to do in the rest of this chapter is to show that even if it did not create conceptual-philosophical problems, the inner screen notion is at odds with some well-established facts about human vision. In the course of this discussion I will present a number of experimental results that will serve us later when I will return to the Cartesian Theater in connection with the idea of a “mental image”, for the mental image, as it is understood by many contemporary thinkers, relies heavily on the assumption that there is a Cartesian Theater with a screen and a projector and a homunculus or “mind’s eye” sitting in the audience. I will return to this assumption later, especially in Chapters 6-8.

While a misinterpretation of our phenomenal experience may be what drives us to the assumption of an inner display in the first place, it is not the only consideration that keeps many psychologists committed to it. In a great many cases the content of phenomenal experience also has observable consequences in objective measures of visual processing: In fact phenomenal experience plays a central role in the methodology of visual science insofar as theories of vision are typically concerned with explaining the nature of our phenomenal experience. This in itself raises problems that will occupy some of our attention later. For now

¹ In an earlier time there was also some concern about how we manage to see the world rightside-up when the image on the retinas are upside-down. These days this no longer bothers most people because they implicitly understand that what counts as *up* for us is determined by how the brain *interprets* the retinal image and how it coordinates properties of the image with our actions on the world. This downplaying of physical image-properties in relation to both our phenomenal experience and our motor behavior towards the perceived world marks the beginning of an appreciation that information processing and phenomenal experience are a long way from the retina and that much goes on in the interval.

let us stay with the question of why many scholars of visual perception tacitly assume an inner display in attempting to understand how vision works.

1.3.2 Some reasons for thinking there may be an inner display

The overriding reason for believing in an inner display or image or Cartesian Theater, is that the information on the retinas is so totally discrepant from the phenomenal experience of perception. We have already alluded to the peephole scope of the retinal information, its rapidly changing contents, and its unnoticed blind spot that gets filled in for phenomenal experience. Then there is the frequently noted phenomenon where familiar forms appear to get filled-in when parts of them are occluded, as in Figure 3 below, or even unfamiliar forms appear to be filled-in in illusory contours (illustrated in Figure 4) or in cases of so-called amodal completion (Chapter 2, Figure 2-5), which will be discussed later. This “filling in” is a subjective impression in the case of the blind spot, since there is no functional information available for the particular part of the scene corresponding to the scotoma. But in other cases it’s not so obvious that *no* information is involved, even though there may be no local information at a particular site. For example, in the case of partially occluded figures such as below, it is possible that the mind provides the missing information and actually restores the image, if not on the retina then at some subsequent locus in the brain. In the example below the missing parts of the words don’t just seem to be there, they are functionally present insofar as we are actually able to recognize and “read” the words.



Figure 1-4: Despite the large amount of missing information, the familiar words are easily discerned. Are they “restored” by the visual system on some inner display?

So-called illusory or virtual contours (such as those seen in the figure on the right of Figure 1-5) not only have a phenomenal existence, but they act in many ways as though they were actually present in the figures. Take, for example, the Pogendorff illusion in which an oblique line that crosses a column appears to be broken and not aligned with its geometrical continuation. When subjects are asked to adjust one part of the diagonal line so it appears to be continuous with the other part, they tend to set the lower line systematically higher than it should be for geometrically correct continuation. This phenomenon happens equally when the column is made up of virtual or illusory lines as it is in Figure 1-5 below.

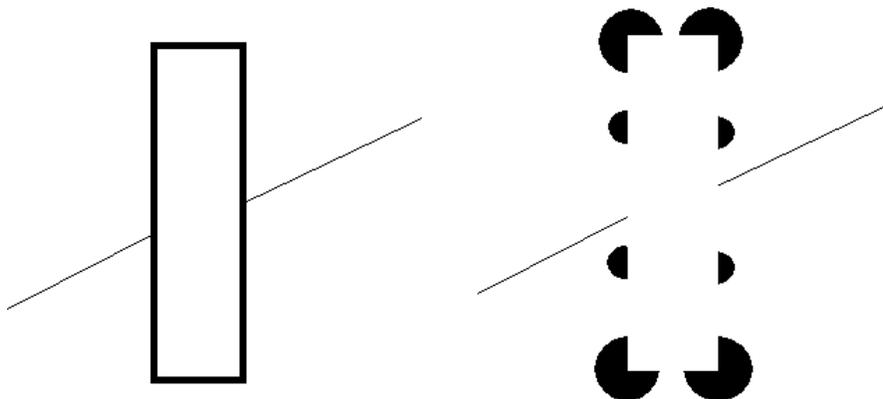


Figure 1-5. The Pogendorff Illusion works equally well with virtual (illusory) lines as with real ones. The oblique line in both figures looks continuous even though it is not.

Similarly one can see that the “completed” figure is the one that is visually prominent by considering the problem of finding a given figure in a jumble (a kind of Where’s Waldo® game). Consider the simple figure shown here:



Can you find that target in the jumble in Figure 1-6? You may find it easy to identify one such instance, despite the fact that part of it is actually cut off by a circle. But there is another one that is harder to find because the visual system has “completed” it as a square.

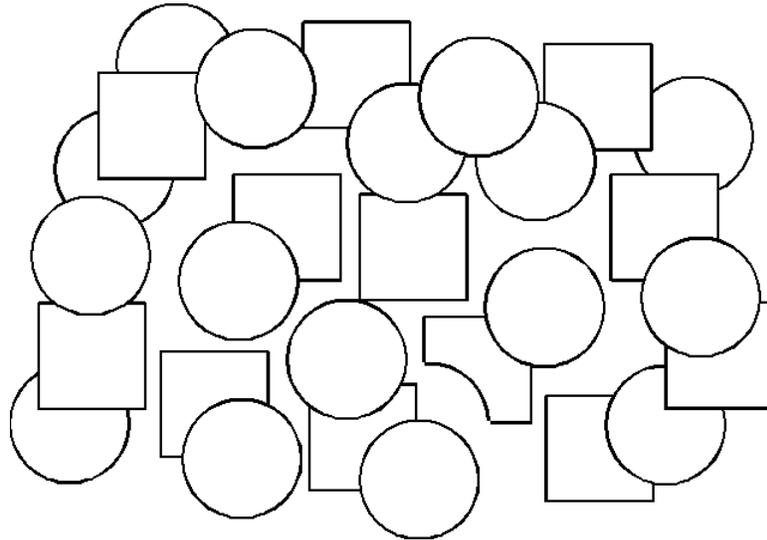


Figure 1-6. The “search set”. Find two copies of the target in this set. Have the figures been “completed” in some inner display, making the target that appears to be partly occluded harder to find?

There are also many examples where visual properties are interrelated or *coupled* (to use Irvin Rock’s term). Such visual “couplings” may depend on aspects of the perception that do not exist objectively on the retina. For example, the virtual rectangle created by the array of Pac-Man figures in Figure 1-5, not only has the phenomenal content of being an opaque surface in front of some disks, it also appears to be brighter than the background by objective psychophysical measures as well as leading to the Pogendorff illusion shown in the figure. Why would these particular properties (and a large number of other such objective properties) occur *at particular locations* in the display if not because the illusory lines and the surface they define are *actually* present somewhere in the brain and provide the locations where the effect is localized? The “somewhere” in all these examples ends up being the “mental image” or the Cartesian display.

The idea that the mind gets to look at a display that has been filled in and built up from separate segments is widespread. Not only is such a display thought to cover a larger spatial extent than the fovea, but it also appears to involve visual information that may have been present in the recent past but which is no longer present on the retina. In an interesting and thoughtful essay, Julian Hochberg (Hochberg, 1968) makes a case that many principles of visual organization seem to hold over arrays larger than those on the retina. He speaks rather cautiously and hesitantly of a visual “immediate memory”, though making it clear that such a storage does not retain information in what would quite qualify as a strictly *visual* or *image* format. One reason why Hochberg speaks of a visual memory at all is that visual forms can be discerned when there are no literal forms on the retina – at least not in the sense of contours defined by luminance gradients – and so it is natural to assume that they must be in some post-retinal storage. Here are some examples. In the following I use the neutral term “discern” instead of “perceive” since we don’t want to prejudge whether these count as bona fide cases of visual perception.

- Forms can be displayed as contours, dotted lines, or in some cases just the high-information regions, such as vertices alone.

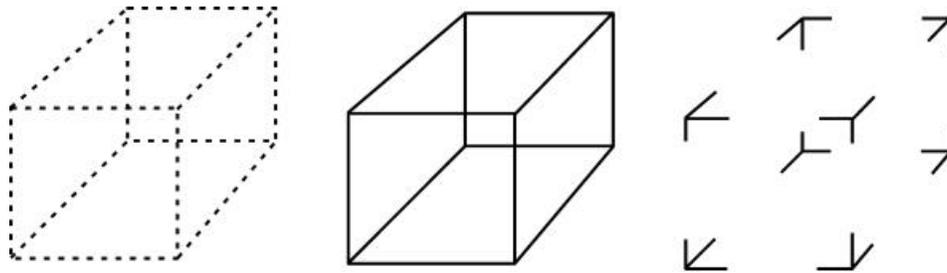


Figure 1-7. Different ways to show a Necker Cube that exhibit equivalent information.

- Forms can be discerned in a field of elements if the subset of elements that lie on a particular (virtual) contour are readily distinguishable – say if they are a different shape or brightness or color from the other elements, or if they are briefly displaced (or wiggled) back and forth. Once again in this case the form is perceived providing only that the differences are sufficient to constitute what are called “popout” or automatically-registered differences (more on this in chapter 5). Figure 1-8, below, is an example.

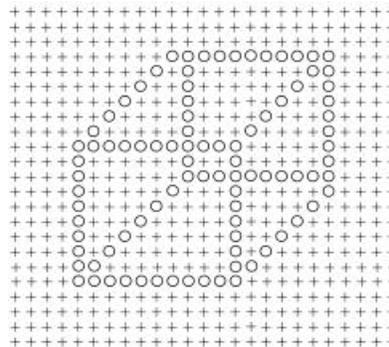


Figure 1-8: The same shape as shown in Figure 1-7, but created just by local feature differences. Can you see the form?

- Forms can also be discerned in random-dot stereograms – an interesting form of visual display invented by Bela Julesz (Julesz, 1971). In these binocularly viewed displays, the perception of a form derives from the retinal disparity of certain regions of the display. Neither eye receives form information, but the distribution of random dots on the two eyes is such that when most of the points on the two retinas are matched, the location of the remaining points in a certain region are discrepant by some retinal distance. This discrepancy (known as “retinal disparity”) is what produces the effect of stereo depth in normal binocular vision. When the region of discrepancy is chosen to correspond to a contour region, such as one that defines the line drawing of a Necker cube, a cube is perceived.
- Forms can even be discerned if an opaque screen with a narrow slit in it is moved back and forth over a stimulus in a device known as an “anorthoscope.” If the motion is fast enough it appears to “paint” an image that can be discerned – though whether they are actually “perceived” remains an open question. It is reportedly even possible to recognize a form if the stimulus is moved back and forth behind a screen, so that the form is viewed as a stream of views all occurring at a single vertical line on the retina (although the phenomenal impression is not nearly as clear). Perception with these sorts of presentations has been referred to as the “eye-of-the-needle” or the “Zollner-Parks” phenomenon – see Figure 1-5 or Figure 1-16 for an illustration of forms presented through an anorthoscope.

The same form can be discerned, more or less clearly and vividly, in all these cases despite the enormous differences in the physical stimuli and despite the fact that in some of the presentations, such as the random-dot stereograms and the anorthoscopic presentation, *no form at all is present on the retina*. What is important, however, is not just whether the form is recognized, but whether it exhibits the properties associated with what we call early (automatic) vision. As we will see, some of these modes of presentation do, whereas others do not, depending on how quickly they are presented and whether they are distributed over a fixed space. These signature properties of vision include the familiar Gestalt grouping principles (such as grouping by proximity, similarity, common fate, and so on). They also include the *spontaneous 3D organization* of certain contours, the *perceptual coupling* among properties (particularly the coupling between how parts are interpreted or labeled, see the discussion of labeling in Chapter 3 – especially section 3.1.1.1) so that how one part of a form is interpreted depends on how another part is interpreted, and *spontaneous reversals and apparent motion in 3D*, as we saw in the case of the Necker Cube (notice that this coupling effect is experienced in both Figure 1-8 and Figure 1-8; when the figure spontaneously reverse, the interpretation of individual edges changes, as well as the relative size of the faces, which change depending on which face is perceived as the front and which the rear face). Other properties of early vision are discussed in Chapter 2 (especially section 2.3.2).

Although, as we will see in the next chapter, many of the details of these claims are problematic in important ways, the basic idea appears sound enough: Various principles of form perception and of visual organization seem to apply to a unit of display that goes beyond the current instantaneous content of the retina, and so must necessarily include visual memory. This provides some reason to think that visual processes apply to the contents of something like a “visual store”, which is precisely the inner display we have been arguing against. What these examples do not demonstrate, however, and what I shall argue is not true, is that the information in the visual store is pictorial in any sense – i.e., the stored information does not act as though it was a stable and reconstructed extension of the retina.

Other reasons for postulating an inner display are sometimes given as well. For example, (Kosslyn, 1994) justifies his postulation of an inner screen (which he later uses to develop a theory of mental imagery in which images as projected onto this screen) by arguing that such a display is independently needed to account for visual stability and for the ability to recognize objects regardless of their location on the retina or their retinal size.² According to this argument, if you have a central display you can expand or contract patterns or move them around (or, equivalently, move an “attentional window” around) so that they can be brought into correspondence with a template in a standard location on the inner screen, even if you can’t do so on the retina.

But as we have seen there are plenty of reasons to reject the idea of a central display as a way of fusing partial and fleeting images into a coherent large-compass percept. Most vision scientists do not talk about an inner display, and may even be embarrassed when confronted with the fact that their way of talking about certain phenomena appears to tacitly assume such a display. A few, like Kosslyn, actually do explicitly endorse an “inner picture” assumption. (Kosslyn, 1994) provides a clear case of someone who has built an elaborate theory around the assumption of an inner screen. As he puts it (p85); “...if certain properties of the world are internalized, are embodied by properties of our brains, many problems may be solved relatively easily.” This assumption will be brought under scrutiny in various places in this book. Later in chapters 6 and 7 I will examine the plausibility of a theory of mental imagery that posits the projection of images onto the inner screen. For the time being I wish simply to look at the reasons why vision itself does not require such a postulate, and indeed why it ought to shun it despite its intuitive plausibility.

² In fact there is evidence that even this apparently bland assumption – that we can recognize patterns irrespective of their retinal locations – may be false in some circumstances. (Nazir & O’Regan, 1990) showed that if the learned pattern was of a particular size and retinal location it generalized very poorly to patterns of different sizes and retinal locations. Also (Schlingensiepen, Campbell, Legge, & Walker, 1986) showed that even simple patterns could not be distinguished without eye movements so that a static retinal location is a hindrance to pattern perception. Learning of other perceptual phenomena, such as stereopsis, generalize very poorly to new retinal locations (Ramachandran, 1976) and retinal orientation (Ramachandran & Braddick, 1973).

1.4 Some problems with the Inner Display Assumption: Part I: What's in the display?

1.4.1 How is the master image built up from glances?

We have seen that a form is perceived even when the retinal image is highly impoverished (and perhaps even nonexistent) and even when it is known that the retinal information is not being communicated to the brain (as in the case of the blind-spot or off-foveal parts of the display). We have also seen that off-retinal information combines in some ways with the retinally-present information to produce a characteristic percept. All this suggests that information processed by the visual system not only comes from the retina (or the fovea) but also from some form of visual storage. But how does the information get into the storage? For years the common view has been that a large-scope inner image is built up by superimposing information from individual glances at the appropriate coordinates of the master image: As the eye is scanned, an inner projector moves in registry with the eye and paints the retinal information onto the inner screen. The general idea behind this view is illustrated in Figure 1-9 below. As the eye moves over a scene the information on the retina is transmitted to the perceptual system, which then projects it onto an inner screen in the appropriate location, thus painting the larger scene for the “mind’s eye” to observe.

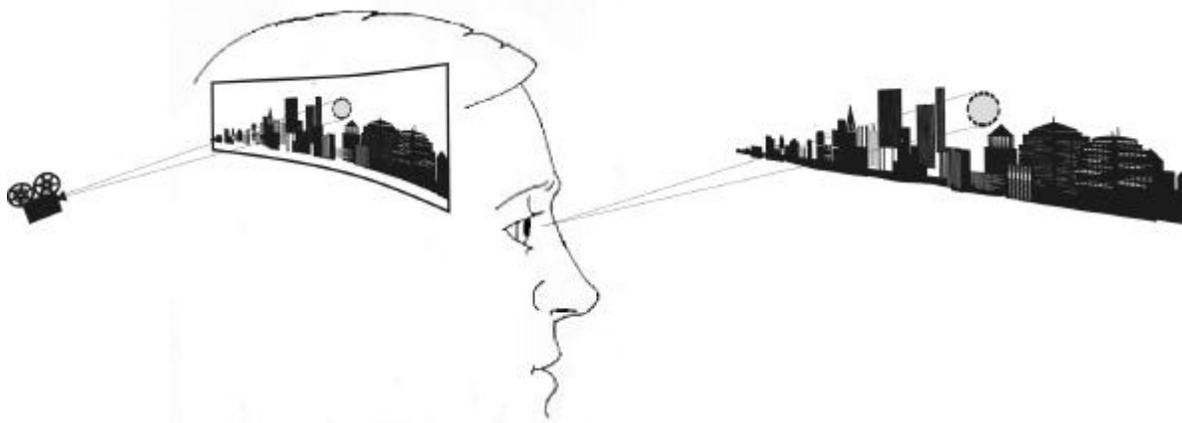


Figure 1-9. The “inner display” explanation of why we appear to see a large panorama, despite the fact that the information the brain is receiving is limited to a small region of the field of view. The idea is that an inner projector moves in registration with the motion of the eye and creates a large and detailed inner image of the scene.

This sort of mechanism would clearly explain both the apparent completeness and stability of the percept. This view even had some support from neurophysiological evidence showing that the locus of various visual responses in the brain (the receptive field of visual neurons) shifts when the eye is moved. This theory also received support from a widely accepted idea, called the “corollary discharge” theory which claims that when the eye is commanded to move, a copy of the eye-movement command (called the “efference copy”) is sent to the “inner projector” and determines where the new information is to be overlaid (an idea that goes back to von Holst & Mittelstaedt, 1971/1950). It has been claimed, for example, that when one tries unsuccessfully to move ones eyes (when, for example, the eye muscles are injured and unable to carry out the command to move) the world appears to move in the opposite direction since the efference copy of the command tells the projector to place the perceptual signal from the eye where the eye would have been looking had it worked properly. It should be noted here that there is much wrong with this story, not the least of which is that there is serious doubt that the position of an object appears to move to the left when the eye is commanded to move to the right but is unable to. It appears that this widely-cited phenomenon may be false – as the amazing experiment by John Stevens and colleagues (Stevens, Emerson, Gerstein, Kallos, Neufield, Nichols, & Rosenquist, 1976) seems to show. Stevens had himself totally paralyzed with curare (except for part of his arm through which he was able to signal his replies – or any

calls for help!) and performed the experiment in an iron lung. He reported no reverse motion of his percept when he attempted to move his eyes.

More recently, all aspects of this inner-display view have run into serious difficulties and now the notion of superposition appears to be totally untenable. There are a number of reasons for the demise of this view of how the stable master-image is built up.

- Recent studies using eye-tracking equipment have provided some rather surprising findings regarding the amount of information taken in at each glance. (Carlson-Radvansky, 1999; Grimes, 1996; Irwin, 1991; Irwin, 1993; Irwin, 1996; McConkie & Currie, 1996) have shown that very little information is retained from one glance to another when the eyes move, nor even when the eyes do not move but the display disappears briefly (Rensink, 2000; Simons & Levin, 1997). If the scene being viewed is changed in even major ways during a saccade the change goes unnoticed. Observers do not notice changes in the color or location of major parts of a scene (unless they were explicitly attempting to examine those parts), nor do such changes have any consequence on what is perceived. (Irwin, 1996) showed that very little qualitative information is retained about a simple pattern of dots from one glance to another, and the location of only about 4 or 5 salient points is retained.³
- A sequence of retinal images does not appear to be superimposed. Experiments have been carried out (O'Regan & Lévy-Schoen, 1983) in which different patterns were presented at known retinal locations before and after a saccade. What observers saw in these cases was not the superposition of the two patterns, as would be expected from, say, the presentation of the figures shown in Figure 1-10, where there is a saccade between the two parts of the displays.

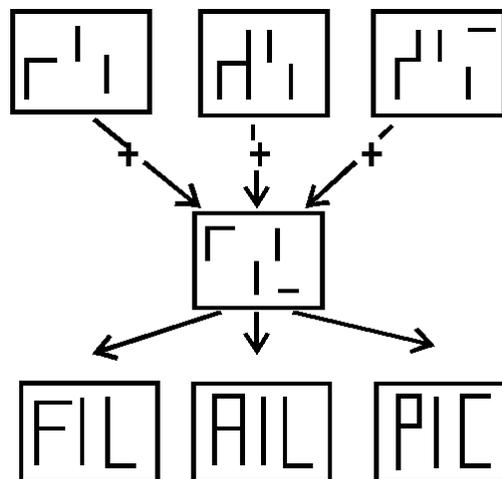


Figure 1-10: In this study described in (O'Regan & Lévy-Schoen, 1983) an eye movement occurred between presentation of the top figure and presentation of the middle figure. If the two were superimposed, one of the three bottom ones would be seen. There was no evidence of such superposition.

1.4.2 What is the form of non-retinal information?

Despite Hochberg's observation that off-retinal (stored) visual information shows some of the principles of perceptual organization, many important visual properties are not observed when the critical interacting parts are not simultaneously in view, and even those that are observed do not have the phenomenal clarity that they have when they are actually viewed retinally, raising the question of whether they are seen or inferred (see next section). For example, many of the signature properties of visual perception – such as the

³ Recent evidence suggests that accurate information tends to be available from places close to where the eye fell during recent fixations while scanning (Henderson & Hollingworth, 1999). Nonetheless the fact remains that what is retained in immediate memory is generally far from being the sort of detailed pictorial information required by the picture-painting or superposition view.

spontaneous interpretation of certain line drawings as depicting 3D objects, spontaneous reversals, recognition of the oddity of “impossible objects” such as those in Escher drawings or the so-called Devil’s Pitchfork (Figure 1-11)– do not occur if the drawings are made large enough so that the ends are not simultaneously present on the retina. Thus, for example, the well known figures such as the Necker Cube do not appear as a reversing 3D shapes and the Devil’s Pitchfork does not seem so odd when it is drawn elongated and viewed in such a way that the ends are not simultaneously in the fovea (Figure 1-12). Since the phenomenal percept in these cases, as in all perceptual experience involving eye movements, arguably does cover the entire object⁴, the entire object is presumably displayed on the inner screen or the master image.

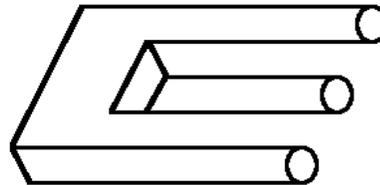


Figure 1-11: In the figure above, it takes just a brief inspection to see that something is amiss – this “devil’s pitchfork” cannot be given a consistent 3D interpretation because the way the edges are interpreted has to be different at the two ends; the edges receive incompatible labels from local interpretations

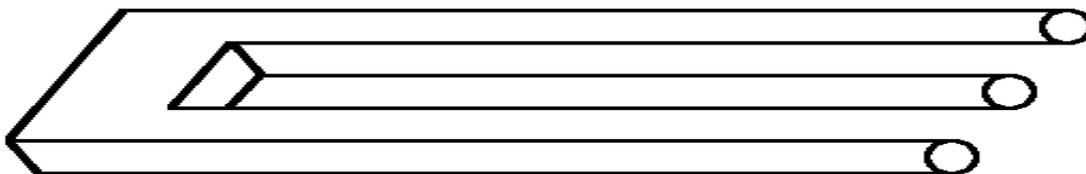


Figure 1-12: In this version, if the picture is held close up so the two ends are not simultaneously projected onto the fovea, it is not nearly so obvious that something is wrong. Integrating the information from the two ends requires an appeal to memory; it is not just a matter of “painting” the larger picture onto the master image.

Other evidence for the claim that off-retinal (or perhaps I should say off-foveal) information does not function in the same way as foveal information was obtained by (Peterson & Gibson, 1991; Peterson & Hochberg, 1983). Using figures such as those in Figure 1-13 these investigators showed that the figure maintains its ambiguous status and exhibits reversals even though a part of the figure is unambiguous and therefore the entire figure would be unambiguous if the relevant cue that disambiguates the figure were taken into account. In the figure on the left, the point marked “1” disambiguates the figure so that its shape must be that depicted by the middle figure. Yet when attending to point “2” the viewer sees the orientation

⁴ The question of what is contained in the “phenomenal image” is problematic, to say the least. I am using the term the way many theorists do, although some careful observers, like Hochberg, make a point of emphasizing that the phenomenal experience of what is sensed (i.e., on the fovea) is quite different from that in memory. Thus in describing what he saw through the anorthoscope aperture view (such as shown in Figure 1-15), (Hochberg, 1968, p315-316) says, “Let me describe what our ... aperture view looks like to me: In the aperture itself, [is] a clearly *sensory* vertical ribbon of dots ... ; the ribbon of dots – still quite clear – is part of an entire (largely *unseen*) surface of dots that is moving back and forth *behind* the aperture... there is no real sensory quality to either the shape or its background, where these are occluded by the mask. I’m completely certain that I only *see* those portions of the shape that are behind the aperture at any moment, but I’m equally certain of the extension of the shape behind the mask. Is this ‘perception,’ ‘apprehension,’ ‘Imagination?’ Perhaps we’re not dealing with perception at all, in these situations. Maybe merely *knowing* what the pattern is, is sufficient to elicit the different tridimensional ratings, regardless of how this knowledge is gained.”

of the figure alternate between the version shown in the middle figure and the one shown in the figure on the right.

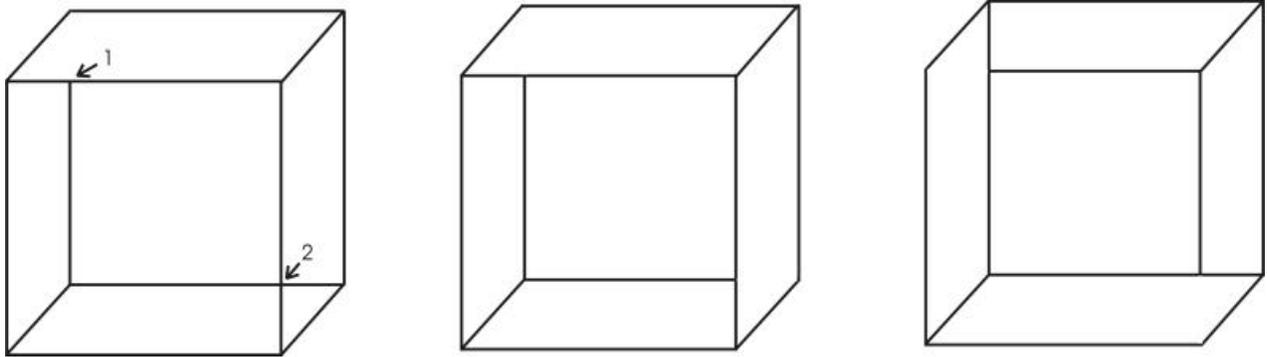


Figure 1-13: The figure on the left is globally unambiguous, yet when attending to the point marked “2” it remains ambiguous between the two orientations shown in the middle and right figures. (Based on Peterson & Gibson, 1991).

In this example, the point labeled “1” should be able to disambiguate the entire figure since it makes the local portion of the figure univocal. Yet it does not appear to affect the way the figure as a whole is perceived; if you focus at the point labeled “2”, the figure remains ambiguous. In fact if the distance between the cue and the ambiguous parts is great enough it has little effect in disambiguating the percept, as can be seen if we elongate the globally unambiguous figure (see Figure 1-14).

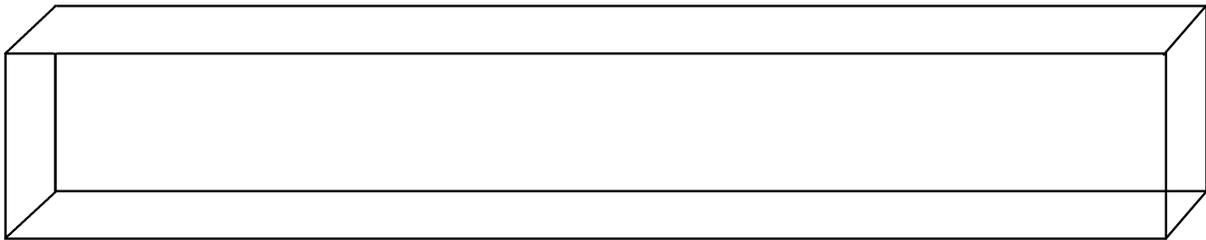


Figure 1-14. This figure, in which the disambiguating cue is further away from the locally ambiguous parts, is even less likely to be perceived as the unambiguous box such as the middle figure of Figure 1-13.

The same point can be illustrated by presenting visual patterns in rapid sequence to the eye. As we already remarked, in such cases observers typically feel that they see some larger integrated pattern. I have already mentioned the anorthoscope, or the Zollner-Parks phenomenon, studied extensively by (Parks, 1965; Rock, 1981). In these studies, a pattern, viewed through a moving narrow slit that travels back and forth across the pattern, appears to be seen if the slit moves sufficiently rapidly. In fact it has even been reported as perceived, though not quite as readily or clearly, if the slit is held fixed and the pattern is moved back and forth behind it. Of course the moving slit version could involve something like a persistent “retinal painting” by the moving slit display, the way painting a scene on a TV set results in a display larger than the moving dot this is unlikely in the fixed-slit moving-display version of the experiment. However, some of the studies controlled for eye movements that would be required in order to paint the figure across the retina. Also (Rock, 1983) showed that “retinal painting” is not in itself a general phenomenon, since simply moving a point of light along a path identical to the one that was traced out in the anorthoscope experiment does not yield a perception of the form. It turns out that the slit itself must be visible in order to get the anorthoscope effect. Not only must the slit be seen in outline, but it must also be seen to be occluding the figure as the screen moves over the figure. If the visible portions of the form (the little bits that can be seen through the

slits in Figure 1-15 and Figure 1-16) do not extend to the very edge of the slit the effect is not observed (as illustrated in Figure 3-11, to be discussed later).

Since the anorthoscope effect does not appear to be due to retinal painting, the natural assumption is that the pattern is instead being painted on the inner image, using some unspecified cues as to the motion of the figure behind the slit. But there are many reasons to reject such a view. One is that the ability to see the pattern in the case where the pattern is moving and the slit is fixed depends very much on the memory load imposed by the task of tracking the pattern. For example, in a series of unpublished studies, Ian Howard showed that patterns in which fewer features had to be tracked as they moved across the slit were identified more readily than ones that required more features to be tracked, even when the pattern was actually the same. Thus for example, in Figure 1-15, shapes such as the E was harder to identify than the same shape lying on its back: the former requiring that three segments be tracked as they move behind the slit, while the latter requires only one (together with a count of how many verticals went by). So the image is not just being “painted” on the master image, but must be remembered in a way that is sensitive to how many items there are to recall.

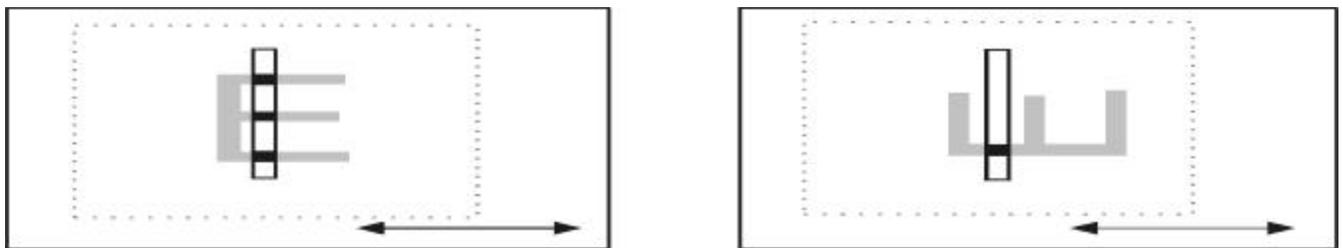


Figure 1-15: The anorthoscope effect, with slit moving back and forth in front of the pattern. The pattern is more easily perceived when there are fewer segments passing in front of the slit (example due to Ian Howard).

Figure 1-16 shows more clearly what must be remembered as the shape is moved past the slit. In this example, the task is to say whether there are one or two separate curves in the partially seen shape. Clearly what an observer must do is keep track of the *type* of each line segment as it passes by the slit. This keeping track of line types – and not the operation of the visual system – is precisely what we shall claim is the basis for all of the demonstrations of “seeing” shapes through the anorthoscope. This type-tracking will be discussed in Chapter 3 in terms of the notion of “label propagation”. Once again in the forms show in Figure 1-16 the task is easier when the forms are turned by 90 degrees, since fewer labeled lines must be tracked in that case.

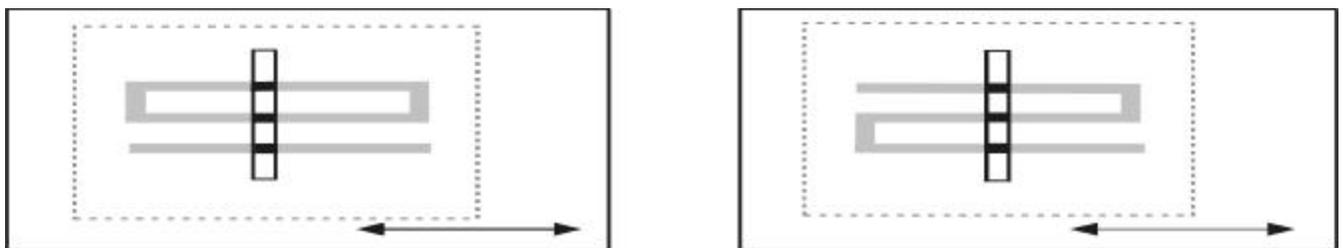


Figure 1-16: Another anorthoscope task: How many distinct line segments are there? In this case the two displays are identical in terms of their inventory of features: Discerning which has one line segment and which has two requires keeping track of which currently-visible segment was connected to which in an earlier part of the viewing sequence.

Julian Hochberg (Hochberg, 1968) conducted related studies involving serial presentation of patterns. He presented sequences of vertical slices of ambiguous figures, such as the Necker cube, at various speeds. There were two conditions of slicing up the image. In one case it was sliced up so that each slice contained

complete vertices. In the other case, slices were made through the tips of the vertices so that the slices contained primarily of straight-line segments (thus breaking up individual vertices in the process). The slices were presented at different speeds. Hochberg found that at fast speeds (around half a second to present 6 slices) the figures were perceived equally easily for both types of slices, consistent with other findings of a very short term visual buffer. But at slow speeds (more like natural viewing of these figures, in which the entire figure takes 2-3 seconds to examine), only the slices that kept vertices intact provided the information for the perception of tridimensionality.

Other similar studies showed that the order in which parts of a figure were displayed through a stationary peephole made a difference in how difficult it was to perceive the figure. For example, (Hochberg, 1968) also studied the perception of anomalous (“impossible”) figures when the figure was presented in a piecemeal fashion. He found that anomalous figures (such as Figure 1-17 below) could be detected in sequential presentations providing the presentation sequence was one that allowed observers to trace the type of the edges past ambiguous vertices until they reach a vertex where those labels are inconsistent with the requirements of a possible 3D vertex.

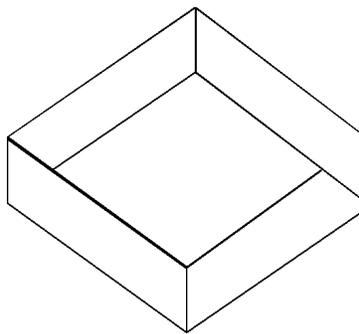


Figure 1-17. Simple “impossible figure” studied by (Hochberg, 1968) with sequential presentation.

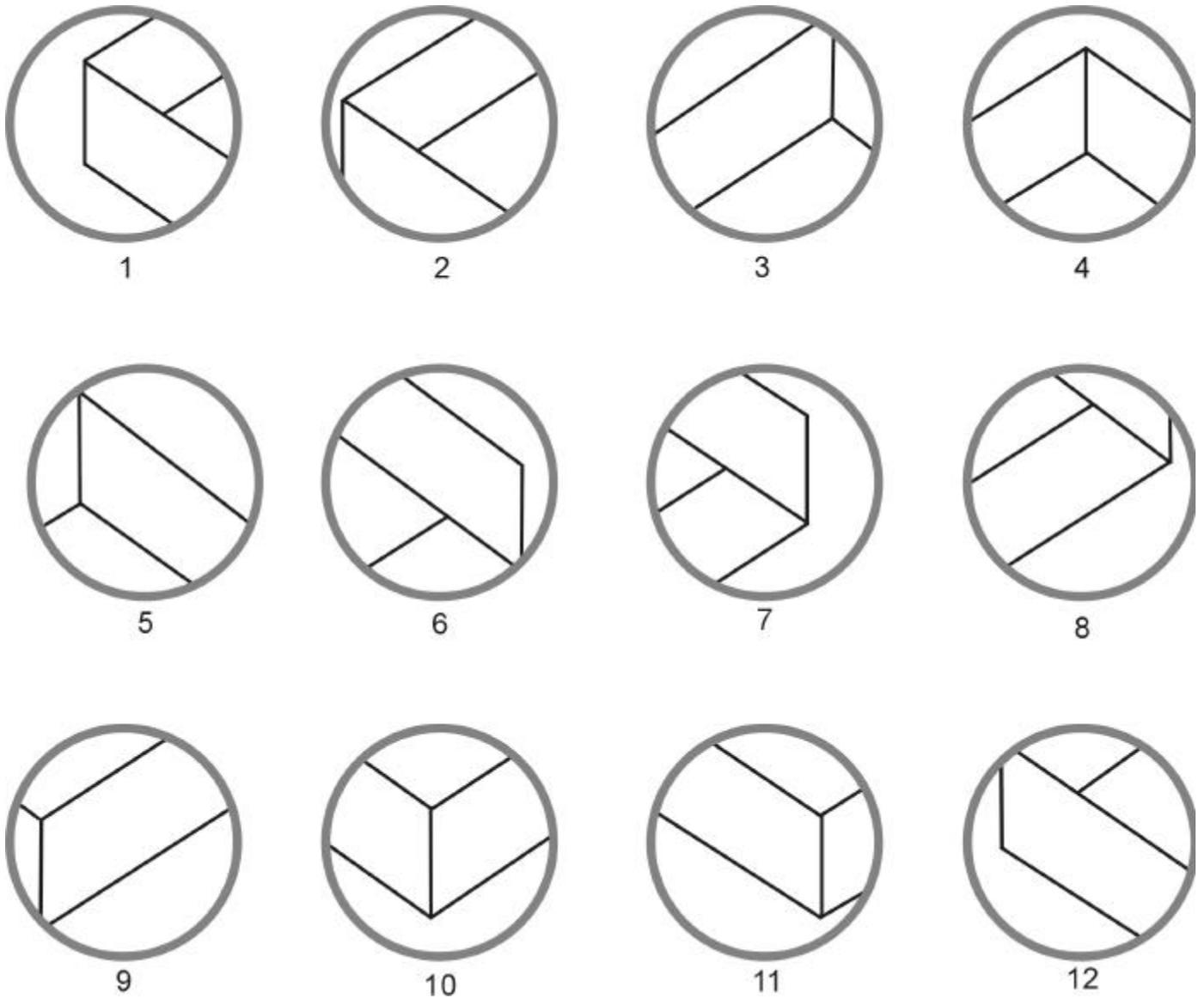


Figure 1-18. Sequence of views similar to that used by (Hochberg, 1968). Observers were able to detect that the sequence is from a drawing of an impossible figure only if the sequence was presented in the right order.

An example of one sequence that does enable detection of the anomaly is shown in Figure 1-18. In this case, however, we do not need to assume that a picture of the global pattern is being built up because a much simpler explanation is available. It is the idea that observers are keeping track of the type of each line or edge⁵ and tracking this edge-type from vertex to vertex. The process is more like observers thinking to themselves: “I see this vertex as concave up, so that this edge here must be an outside concave edge and must continue to be that when it gets to the next vertex, but if *that* edge is an outside convex edge then *this* connecting edge must be a concave outside edge as well ...” and so on. In this way, if the first vertex is seen to reverse then the rest of the labels change to maintain consistency. Note that such reasoning involves indexical (locative) terms like “this edge” and “that vertex”. For such a reasoning sequence to be possible

⁵ The term “line” is generally used in reference to 2-D visual features. When lines are interpreted as parts of 3-D objects they are more appropriately referred to as “edges.” I will try to maintain this distinction, despite the fact that whether something is a line or an edge is often unclear in many contexts. The same is true of the pair of terms “vertex” and “junction” with the former being a 2-D feature.

there must be some way to refer to particular elements in the scene, and that indeed, is the focus of a theory of visual indexing to which we will return in chapter 5. For the present purposes I wish merely to point out that the Hochberg experiments, like the anorthoscope examples discussed previously, all point to the importance of the notion of labeling features in a scene and tracking the labels along spatially contiguous elements (such as edges or surfaces) so as to determine whether they are consistent with labels assigned in other parts of the pattern.

The idea of tracking the labels assigned to edges helps to explain why some sequences are easier to see (or perceive as anomalous) than others. In addition, this labeling idea is in fact consistent with a body of research in computational vision that I will describe in some detail in Chapter 3 (see section 3.1.1.1). In that context I will relate this labeling technique to an important question that arises concerning how a representation of a 3D world can be reconstructed given its highly incomplete and ambiguous 2D retinal projection. The technique developed in computational vision involves assigning possible sets of labels to the elements in a scene and then pruning the set by taking into account the constraints that must hold among such labels (e.g., the label assigned to an edge at one vertex must be a possible label assign to that same edge at another vertex).

This provides an alternative way of characterizing the “signature” visual phenomena that led Hochberg to suggest that a “visual buffer” holds information in pictorial form. Such visual phenomena as spontaneous 3D interpretation, spontaneous reversals and detection of impossible figures can be done by label propagation. This does not require that pictorial information be stored – only that there be a way to keep track of the label assigned to a *currently-visible* edge as some vertices connected to that edge come into view and other vertices go out of view. In other words, so long as we can trace a particular edge and track its label continuously over time, we are in a position to interpret the lines as depicting a 3D object or to decide that no such object is possible. Interpretation of line drawings in 3D is a locally-supported process, as the example of elongated figures shows (and as Hochberg has argued as well). The interpretation initially comes from cues provided by individual vertices alone. These assign (possibly ambiguous) labels to lines viewed as edges of 3-D objects, which have to be supported or rejected by connected vertices. This does not require any visual storage of off-foveal visual patterns. All it requires is that for each line segment current in view, there be a record of what label was assigned to it by the vertex that just moved off the retina. This requires tracing, or otherwise identifying, the lines as they appear on successive retinal images. This sort of analysis works perfectly for the anorthoscope examples (the one in Figure 1-16 requires an even simpler set of labels, simply to keep track of whether a particular line had ever been connected to each of the other lines in the figure).

1.4.3 How “pictorial” is information in the “visual buffer”?

As I suggested in the previous section, there god reason for shunning the assumption that information in a “visual buffer” is not pictorial. There is also considerable direct evidence that the information we extract from a scene does not have nearly the richness, geometrical completeness, and uniformity of detail that we associate with any kind of picture. In fact, as Bishop Berkeley argued, visual concepts are abstract and highly variable in its detail, much the way that information conveyed by language is (e.g. we can describe what is in a scene in great detail while failing to mention where the things were or only vaguely describing their general shape, as in “elongated roundish blobs”). If a master inner image was being painted it is clear that it would have to have some very odd non-pictorial properties, such as labeled regions (what Dennett has described as a “paint-by-numbers” quality). As the examples of extended figures above suggests, once the information gets into the visual system (as opposed to still being on the retina) it no longer seems to function the way visual inputs do, in terms of showing such signature properties as automatic three-dimensional interpretation and spontaneous reversals. As we will see later (Chapter 3) merely getting form information, such as where contours are located, into the visual system does not guarantee that it will serve to drive the usual interpretations, such as three-dimensional shape recovery. Indeed we will show evidence that contour information provided by clearly perceptible differences in textures and colors do not always enable the visual system to see the form in 3D or in motion. So even if we want to persist in thinking of a

master inner image, we will have to greatly modify our idea of what sorts of things can be painted on it – so much so that it will become clear presently that it’s not an image at all.

It has been suggested that what we “see” extends beyond the boundaries of both time and space provided by the sensors in the fovea. So we assume that there is a place where the spatially extended information resides and where visual information is held for a period of time while it is integrated with what came before and what is coming in at present. Thus memory is an essential aspect of the master image – it’s what it is for. For this reason, looking at what visual information is stored over brief periods of time⁶ (seconds or minutes) may give us some insight as to what the visual system provides to the cognizing mind. If we examine cases where people’s visual memory is taxed we can get an idea of how much detail and what *kinds* of details are registered there. When we do this we find that the inner image becomes even less plausible as a vehicle for visual representation. Consider the following experimental results (discussed in Pylyshyn, 1978) which suggest that the information provided to the mind by the visual system is *abstract* and is encoded *conceptually*, perhaps in what has sometimes been called *lingua mentis*, or the language of thought.⁷

The first of these examples come from observing children, who are generally thought to have excellent visual memories. The reason that I present examples taken from observations of children is that we are especially interested in certain kinds of “errors” made in generalizing one visual situation to other (usually a pictorial one), and children tend to be less sophisticated about picturing conventions and so make more errors. We are interested in errors because these tells us what patterns the visual system finds to be most alike, and this, in turn, tells us something about how the visual patterns are represented in visual memory. The examples will be presented first as they are illustrated in Figure 1-19 (a) to (e) below. After describing the results I will then discuss the moral that might be drawn from them.

1. In a typical Piagetian task (see Piaget & Inhelder, 1957), a child is shown a tilted glass containing colored water and asked to draw it, or pick out the drawing that most looks like what she saw. In these experiments the child is most likely to select a drawing in which the water level is either perpendicular or parallel to the sides of the glass, as show in Figure (a) below. (Later we will show that adults are not much better at this water-level task!).

⁶ It is generally accepted that the so-called “iconic storage” retains a complete and detailed retinotopic image, though only for about a quarter of a second (Sperling, 1960). This is clearly not the storage system that is relevant to the arguments for an inner screen since our phenomenal visual experience, as well as the sorts of empirical phenomena discussed by Hochberg, apply over a much longer period of time and over a wider region than the retina. Some studies (Posner, 1978) have shown that during the first second or so information is transformed from an iconic to a more abstract (categorical) form. If so, it is this latter stage of storage that is relevant to our present discussion, which just confirms what we have been arguing, namely that information in the visual store is abstract and categorical (e.g. consists of labels).

⁷ In a broad defense of the pictorial view (specifically as it pertains to mental imagery), (Tye, 1991) has criticized these examples on the grounds that (a) they only implicate memory and not the pictorial display itself, and (b) pictures, too, can be noncommittal and abstract. The first of these is irrelevant since one of the ideas I am questioning is precisely the pictorial view of memory representation. Although many proponents of the picture view of mental imagery may have given up on the assumption that long term memory is pictorial, not everyone has, and certainly at the time of my critique such a view was rather widespread (see the quotations in Pylyshyn, 1973). As for the notion that images can be noncommittal and have an abstract character, this is simply a play on words. The way pictures get to have noncommittal content is by appealing to conventions by which they may be “read” like linguistic symbols. Sure, you can have a picture of a tilted beaker (such as in Figure 1-19a) which shows a fluid surface but is noncommittal about the orientation of the surface: You can do it by painting a blur or a squiggle where the fluid level is to be indicated. And then you can say that this information is indeterminate. But the blurring is simply an invitation *not to pay attention* to the part of the figure depicting the surface. It’s like mumbling when you come to the part of the argument you are not sure about which, come to think of it, is exactly what is going on in this proposal. In chapters 6 and 7 we will return to the popular shell game wherein various properties are imputed to the image in order to hide the fact that the work is no longer being done by the picture but by the “mind’s eye” and the brain behind it.



Figure 1-19(a). Sketch of Piaget's finding: A child is shown the figure on the left and recalls one of the figures on the right.

2. If a child is shown a solid block, say a cube, and asked to draw it or to select a drawing that most looks like it from a set of alternatives, the child frequently chooses drawings such as those shown in figure (b), rather than the more conventional isometric or perspective projections (such as the Necker Cube show in Figure 1-7). This idea was first described in (Winston, 1974), and led to experiments reported in an M.Sc. thesis by Ed Weinstein (Weinstein, 1974).

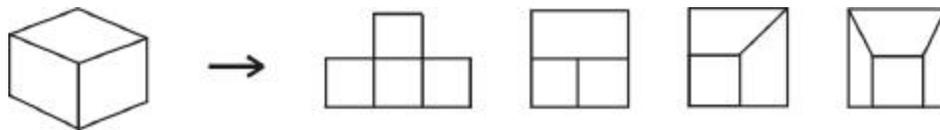


Figure 1-19(b). Another children's recall finding. A child is shown a cube and draws one of the drawings shown on the right of the arrow.

3. It is a common observation that a child will frequently reverse a letter of the alphabet and draw its mirror image, as show in Figure (c). This phenomenon is quite ubiquitous. When presented with any shape and asked to find the same shape among a set of alternatives, a child tend to mistake the shape and its mirror image more often than the shape and a tilted version of the shape. (Adults tend to make this error as well, though not as frequently). These and related studies are reported in (Rock, 1973).



Figure 1-19(c). Children much more often mistake a figure for its mirror image than for a rotated version of that figure.

4. When asked to imitate an action such as placing a small object close to a container like a cup, children more often place the object *inside* the cup rather than beside it, as illustrated schematically in Figure (d). Imitating actions in an interesting way of examining how people (or animals) view the action. No act of imitation is ever an exact replica of the action being imitated. Not only are we incapable of perfect imitation of all muscles and movements, an imitation does not need to be a precise physically duplicate in order to qualify as an accurate imitation. What is required is that the imitation preserve what is essential in the action being imitated, and that in turn tells us something about how the action was perceived or encoded. These studies are part of a series reported in (Clark, 1973).



Figure 1-19(d). Children sometimes make what seem to us like errors when they imitate an adult's actions. Here a child imitates the act of placing a small object beside a cup by placing the object inside the cup.

The other examples are drawn from studies with adult subjects, but they illustrate the same general point.

- Figure (e) shows the results of a study on visual memory for chess positions by (Chase & Simon, 1973). The graph illustrates that when chess masters and novices are shown a mid-game chess board for about 5 seconds, the chess master can reproduce it with almost perfect accuracy, while the novice can only get one or two chess positions correct. But when they are shown the same chess pieces arranged in a random pattern, the two groups do equally poorly. The visual memory superiority of the chess masters is specific to real chess positions.

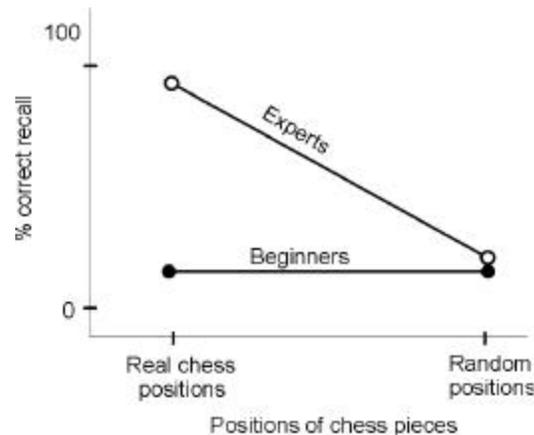


Figure 1-19(e). This graph that chess masters' apparent superior memory of chess positions only holds when the chess pieces are arranged in a pattern taken from a real chess game. When the same chess pieces are arranged in a random pattern the chess masters are no better than novices.

- Figure (f) shows an experiment by Steve Palmer (Palmer, 1977) in which subjects are asked to examine two simple line drawings and superimpose them in their mind (presumably on their master image), then select the drawing most like the superimposed combined image. There is a great deal of difference in how well people do depending on whether or not the two figures fit together as natural subparts to create the complex. It appears that superimposing even simple shapes in the master image is not a matter of mechanically overlaying them: The perceived subpart structure of the resulting figure – whether the two figures form natural groupings when superimposed – matters. Consequently the two top ones are easier to combine than the bottom two in figure (f) to produce the same combined image, shown on the right.

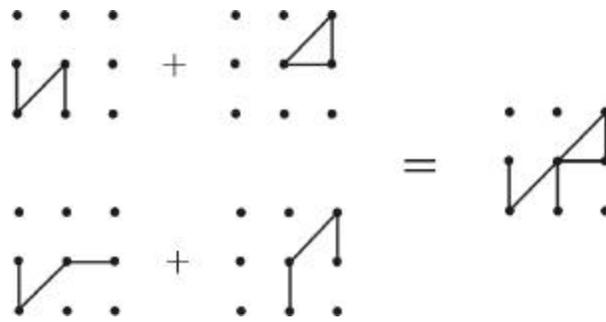


Figure 1-19(f). When observers are asked to superimpose the figures in the first column with those in the second column and tested as to what the combined figure looks like (in this case it's the one on the right) it matters a great deal whether the figures that are combined constitute a "good subpart" of the combined figure (which they do in the top row and do not in the bottom row).

This collection of experiments presents some perhaps surprising findings regarding errors in visual recognition commonly made by observers. What do they have in common and what do they suggest about the way the visual system encodes a visual stimulus? If the visual system constructed a master image that persisted and provided the basis for visual memory, then the errors one would expect would be something like the errors that a template-fitting process might produce. Patterns or shapes that differed least in terms of their geometry should be most often mistaken. But that is not what happens in visual memory, and it's not even what we would intuitively expect to happen. After all, when you miss-recall a scene, such as the appearance of the room full of people at your last party, you do not expect that what you will get wrong will be anything like a pictorial distortion – things moved a bit or shapes altered slightly. In fact in the case of a two-dimensional picture even a slight difference in vantage point would change the geometry radically without affecting what is represented in the image. People are much more likely to mistake a photograph of a room they had seen with one that was taken from a different point of view, than one which contained a different person, no matter how larger the geometrical difference was in the first case. Even if the image were three-dimensional, like a hologram, it would still be too sensitive to unimportant geometrical deviations in relation to meaningful ones. And it is the meaningful properties, which are often carried by very small pictorial details, that our visual system pays the greatest attention to. As a result, what you get wrong in recalling the party scene is you might forget that Jones was to the left of Smith, though you might remember that they were close to each other and were talking. Your memory image, however complete and vivid it might seem to you, is also indeterminate and noncommittal in a large number of ways. You can recall that two people were having a good time without any recollection of what they were doing. And you can have what seems to you like a clear *image* of this state of affairs. It is possible to feel that one has a perfectly vivid and complete image of a situation that in fact is highly abstract and sketchy, and that is where ones phenomenal experience leads one astray. I often feel I have a vivid image of someone's face, but when asked whether the person wears glasses I find that my image was silent on that question: it neither had glasses nor did it lack them, much as the blind spot neither provides information about the relevant portion of the visual field nor does it contain the information that something is missing. You might note that *sentences* (and other language-like compositional encoding systems) have this sort of content indeterminacy property, whereas pictures do not. You can say things in a language (including any language of thought) that fails to make certain commitments that any picture would have to make (e.g., it can assert that A and B are beside one another while failing to say which is to the right or left).

In terms of the examples just enumerated, if children's visual experiences are represented not as pictures but as conceptual complexes of some sort (we will not speculate at this point what some a complex might be like, except to point out that it is more like a language of thought than a picture), then the availability of certain concepts could be reflected in the errors they make. There is no way to represent (i.e. describe) the tilted-glass display without a concept such as that of allocentric-level (or parallel to the surface of the earth). If this concept is not available then there is no way to capture the special feature that distinguishes between the two displays on the right of example (1). So the child is left with choosing some salient pattern as

consistent as possible with what he or she sees, which happens to be a surface that is either parallel or perpendicular to the sides of the glass. Exactly the same can be said of examples (3) and (4). If shapes are represented conceptually, rather than pictorially, distinguishing a shape from its mirror image requires access to the ego-centric concept “left of” or “right of” (try describing a shape in such a way that it can be distinguished from its mirror image without using such terms or their cognates) and these ego-references concepts are slow to develop compared with concepts like *up* or *down* or *sharp angle* or *perpendicular* or *circular*, and so on. I don’t mean the words “up” and “down” and so on, are not available, but the underlying concepts that these words conventionally express (although without the concepts the words could not be learned either).

So long as we appreciate that what the visual system provides is abstract and conceptual, rather than pictorial, we will also not find the other results puzzling. To mimic a movement is not to reproduce it as depicted in an image, it is rather to generate *some* movement (perhaps one that is preferred on some other grounds) that meets the conceptual representation of the movement as it was seen, or as the visual system represented it. Thus if the child represented the action of moving the small object as an action in which the object was placed in some relevant and appropriate proximal relation to a cup, she might choose to place it inside just because she prefers inside-placing (there is certainly evidence that children like to place things inside other things). Similarly the results of the chess-memory and the superposition experiments sketched in (5) and (6) are baffling if one thinks of the visual system as providing a picture that serves as the form of short-term memory. But they are easily understood if one views the memory entry as being conceptual, where the concepts are either learned over the years or are part of the native machinery of visual organization (and for present purposes we need not take a stand on which if these it is). With the right concepts the representation of a scene can be simple and compact and easily remembered (one may say, with George Miller, that it has been “chunked”), even if its geometrical or pictorial configuration is not.

These examples, as well as those discussed in section 1.4.2 strongly suggest that information about a visual scene is not stored in a pictorial form, but rather is stored in a form more like that of a description, which is characterized by variable grain and abstractness and is based upon available concepts. Thus rather than thinking of vision the way it was depicted in the Kliban cartoon in Figure 1-1, one should replace the picture in the thought balloon (shown on the left panel of Figure 1-20) with a data structure such as on the right panel, in a format that is typically used in artificial intelligence applications.

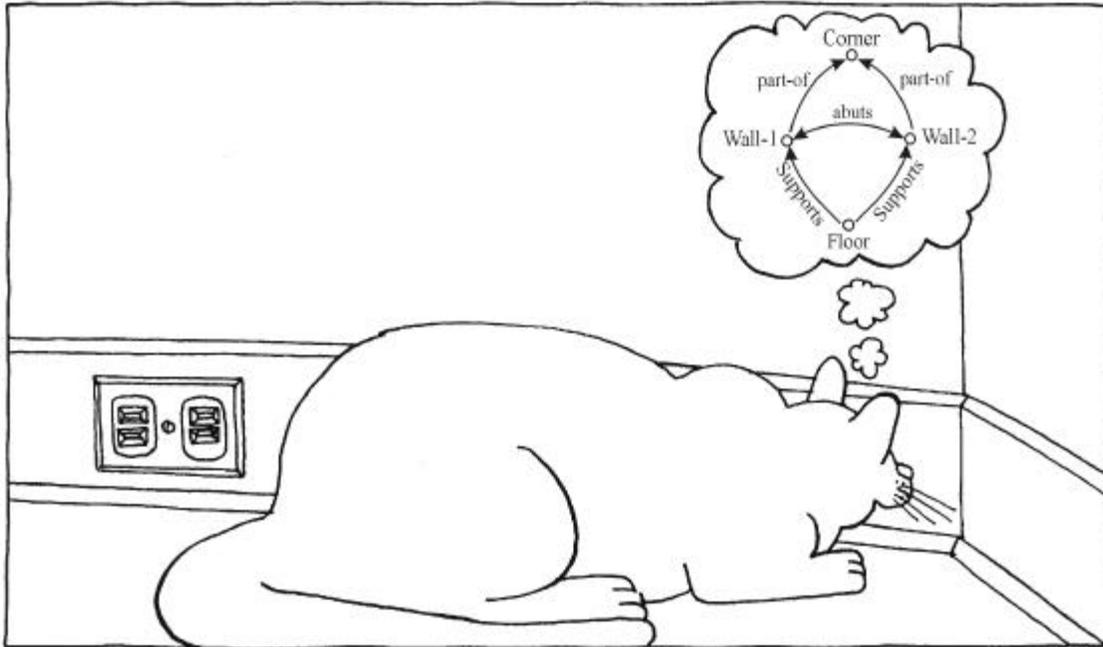


Figure 1-20. Alternative conception of what is in the mind of the cat in the cartoon in Figure 1-1. B. Kliban (American, 1935-1990). From the book *Cat*, by B. Kliban. Use by permission only. All rights reserved. © Judith K. Kliban.

Some further problems with the Inner Display Assumption

Part II: *seeing or figuring out?*

In Chapter 2, we will discuss other methodologies for studying visual perception, and in particular for trying to sort out the thorny problem of which properties of visual apprehension are properties of vision as such, and which are properties of the cognitive system. We will argue that the empirical data are on the side of a clear separation between these processes, providing we are willing to make the sorts of distinctions and idealizations that are ubiquitous in science. But why do we believe that and what are we getting ourselves into if we follow this course? As I said earlier, this book is not about the nature of visual experience, as such. Yet we cannot get away without some comment on this question because visual experience appears to be the main source of data on the operation of the visual system. Even when we appeal to the interaction of visual properties, as we did in some of the examples above, or when we use nonverbal evidence (e.g. pointing, reaching, grasping; use of event-related potentials or galvanic skin responses) about perceived objects and thereby get stronger converging evidence, visual experience remains the reference point against which we measure what we mean by *seeing*. The situation is rather similar to that in linguistics where certain signature properties of grammatical structure, such as intuitions of grammaticality and ambiguity, form the basic data, even though these have to be supplemented by theoretically motivated converging observations and judgments. In the case of vision, we must supplement our use of phenomenal experience as the data of vision because phenomenal experience is not always available (and because we don't want to tie ourselves to the assumption that only consciously experienced percepts constitute genuine vision), and because visual experience is itself a fallible source of evidence. But how can our experience be fallible: are we not the final authority as to how things seem to us? Whether or not we want to claim that we are the final authority on how things seem to us, the question of the *content of our perception* is broader than how things seem to us because, unlike conscious experience, it is a construct that must serve in information processing theories and must eventually comport with biological evidence.

1.4.4 A note about terminology

Many of the examples we have considered so far raise questions about when a phenomenon is truly “visual” and when it is conceptually or logically derived or based on figuring out how the world must have been in order to lead to the information we receive from the senses. After all, it is possible that the reason we can recognize the words “New York” in our earlier example (Figure 1-4) might simply be that we can guess them from the bits of information we can pick up; there may be nothing visual about the process and hence no need to postulate an inner completed display. In the preceding section we claimed that vision and cognition could (and should) be distinguished. But in the everyday use of the terms the two overlap extensively. Consequently there are those who object to using a term, such as “vision”, in a way that is at variance with its general informal use. We use the term “vision” (or sometimes “early vision”) to refer to the part of visual perception that is unique to vision and which is not shared by cognition in general. Such a usage has been viewed by some as, at best, terminological imperialism, and at worst circular since it assumes that early vision is impenetrable when the very notion is defined in terms of encapsulation from cognition.

In defense of the present usage, however, it should be pointed out that it is a perfectly legitimate policy to undertake a scientific inquiry into the nature of visual perception by adopting a term that refers to that aspect of the brain’s function that is distinct and uniquely associated with what goes on in that modality (where the exact bound of the “modality” is also an empirical issue—see note **Error! Bookmark not defined.**). To use the term “vision” to include all the organism’s intellectual activity that originates with information at the eye and culminates in beliefs about the world, or even actions, is not very useful since it runs together a lot of different processes. The same policy was adopted by Chomsky who uses the term “language” or “language capacity” to refer to that function that is unique to linguistic processing, even though understanding natural language utterances clearly involves most of our intellectual faculties. It is also the policy I adopted by (Pylyshyn, 1984a) when I use the term “cognition” to refer to processes that operate over representations of knowledge, as distinct from knowledge-independent processes of the “cognitive architecture”, or when I use the term “learning” to refer to certain cognitively-mediated changes in cognitive states (Pylyshyn, 1984b, p 266-268) or “inference” to refer to any quasi-logical process.⁸ Moreover, the policy is not circular (or at least not viciously so) since it embodies a strong empirical claim, namely, that there exists a nontrivial part of the overall visual process that is impenetrable. The burden of the next chapter is to argue that a significant part of the intuitive (or pre-scientific) sense of visual perception is in fact impenetrable and that this part is also complex and covers a great deal of what is special about vision (we will discuss the question of what the visual system, so construed, outputs to other systems in Chapter 3).

The reason for this terminological policy is the usual one that applies in any science. A science progresses to the extent that it identifies general empirically-valid distinctions, such as between mass and weight, heat and temperature, energy and momentum, and so on. We propose a distinction between vision and cognition in order to try to carve nature at her joints; to locate components of the mind/brain that have some principled boundaries or some principled constraints in their interactions with the rest of the mind. To the extent that we can factor the cognitive system into such components, and can specify the nature of the interactions that are permissible among them, we will have taken a step towards understanding how the system works. For the time being I will take for granted that showing principled macro-architectural components can be a step towards understanding how a complex system functions (assuming that the description is valid). Given this background we can then ask: why should we expect there to be a

⁸ The present policy in regard to the use of the term “inference” differs from that of (Fodor, 1983; Fodor & Pylyshyn, 1981) in that I do not use it to refer to processes that are systematically restricted as to what type of input they may take and the type of principles that they follow. Thus I consider early vision, which follows the sorts of principles sketched in sections 2.3.2 and 3.1.2, to not merit the ascription “inference”. While it might be possible to characterize the operation of the visual system in terms of “rules” these would not in any interesting sense be “truth preserving” or semantically motivated, but would simply describe the wired-in regularities such as any mechanism must possess. As in the case of the term “vision” something is lost by being too ecumenical in one’s linguistic usage, namely one loses the ability to make the distinction between a quasi-logical system of inferences and other sorts of causal regularities.

sustainable distinction between cognition and perception? Or more specifically, why do we think that if we draw such a boundary in a principled way, the part that is not “cognition” will include anything more than the sensors? I devote chapters 2 and 3 to arguing the case in favor of the hypothesis that vision and cognition are largely separate functions (i.e., that vision is what I and others have called a module of the mental architecture, see Fodor, 1983). This, I claim, is a major empirical discovery of vision science of the past 30 years.

1.4.5 “Seeing X” versus “believing that what you saw is X”

There is an important distinction to be made between how you experience a perceptual event and what you believe about your experience, and therefore what you may report that you saw. People’s beliefs are notorious in being filtered through their tacit theories and expectations. Thus it is not clear what to make of such results as those reported by (Wittrich, 1959). According to Wittrich, a number of married people reported that when two people, one of whom was their spouse, walked across the well-known Ames distorted room, the stranger appeared to change in size (the usual experience) whereas the spouse did not. There are several possible explanations for this surprising phenomenon (if, indeed, it is a reliable phenomenon). One (the one that Wittrich favors) is that the perception of size is affected by familiarity. Another is that a highly familiar person can result in an attentional focus so narrow that it can exclude contextual visual cues, such as those provided by the Ames room and by the accompanying person. Yet another possibility is that because of all the emotional connections one has with a spouse it is just too hard to accept that the spouse has changed size while walking across the room. As a result, observers may simply refuse to accept that this is how it appeared to them. It is not always possible to describe “how something looks” in terms that are neutral to what you know, although clearly this does happen with illusions, such as the Müller-Lyer illusion (see Figure 2-3).

Consider the following related example in which a subject’s report of “how things look” may well be confounded with “what I believe I saw” or “how I judge the perceived object to be”. In a classical paper, (Perky, 1910b) reported a study in which observers were told to imagine some particular object (e.g. a piece of fruit) while looking at a blank screen. Unbeknownst to the subjects, the experimenter projected faint images on the screen, Perky found that subjects frequently mistook what they were faintly seeing for what they were imagining (e.g. they reported that the images had certain properties, like orientation or color, that were actually arbitrarily-chosen properties of the faintly-projected image). One way to view this is as a demonstration that when the visual experience is ambiguous or unclear, subjects’ beliefs about their experience is particularly labile – in this case what the subjects sometimes believed is that they saw nothing but had the experience of imagining something. In other cases, perhaps in this same experiment, the converse obtained: subjects believed they had seen something but in fact they had seen nothing and had only imagined it. Various methodologies, such as signal detection theory, have been developed in order to try to drive a wedge between the factors leading an observer to decide certain things and factors leading to their detecting things with their senses (for more on the interaction of vision and “mental images”, such as in the Perky effect, see section 6.5).

The point is that even if “how something looks” is determined by the visual system, what we believe we are seeing – what we report seeing – is determined by much more. What we report seeing depends not only on vision, but also on a fallible memory and on our beliefs, which in turn depend on a number of factors that psychologists have spent much time studying. For example, it is known that the larger the role played by memory the more unreliable is the report. There is a great deal of evidence that what people believe they saw is highly malleable, hence the concern about the validity of eyewitness testimony (Loftus, 1975). The often dramatic effects of subliminal stimuli, of hypnotic suggestion, of placebos, and of mass hysteria rests on the gap (things often do rest on a gap!) that exists between seeing, believing, and believing what one has seen. Indeed it is because of such malleability of reports of experiences that psychologists long ago came to appreciate that research methods – such as double blind testing and the use of unobtrusive measures – had to be designed to control for the fact that honest well-meaning people tend to report what they believe they should be reporting (e.g., the “correct” answer, or the answer that is wanted – the so-called experimenter demand effect). It’s not a matter of deliberately lying, although the very notion of a

deliberate lie came under suspicion long ago with the recognition of unconscious motives (with Freud) and of tacit knowledge, both of which are important foundational axioms in all of the human sciences. What is at stake is not the observer's sincerity, but the plasticity of the belief-determining process. There is no sure methodology for distinguishing between what a person experiences in a certain perceptual situation and what they (genuinely) *believe* they experienced, although we will discuss a number of methods for refining this distinction later.

1.4.6 Reports of what something “looks like”: What do they mean?

There is a further problem with some studies that build on reports of how things look and how this can be influenced by beliefs and utilities and expectations and so on. A problem arises from the fact a phrase such as “it looks like X” is typically used in a way that merges them with something like “My visual experience has convinced me that what I am seeing is X”. The terminology of “appearances” is extremely problematic. Wittgenstein provides a typical eye-opening example of how “looks like” runs together something like appearances and beliefs. The playwright Tom Stoppard tells the story in his play *Jumpers* by having two philosophers meet.

Meeting a friend in a corridor, the philosopher says, “Tell me, why do people always say it was natural for men to assume that the sun went around the earth rather than that the earth was rotating?” His friend said, “Well, obviously, because it just *looks* as if the sun was going round the earth.” To which the philosopher replied, “Well, what would it have looked like if it had looked as if the earth was rotating?”

Examples closer to our immediate concerns are easily found. For instance, it is commonly reported that how big something “looks” depends on the presence of size cues in the form of familiar objects (so that, for example, when you are shown a photograph of an unfamiliar shape it is common to include something familiar, such as a person or a hand, in the photograph). But this may well be a different sense of “looks like” than what is meant when we say that in the Müller-Lyer illusion one line looks longer than the other. In the case of the “perceived size” of an unfamiliar object, the object may not actually look different depending on nearby size cues, it may simply be judged to be a different size.

Sometimes claims that some stimulus is “seen” in a particular way have been contested on the grounds that perception and inference have been conflated. For example, a disagreement arose between Theodore Parks and Ralph Haber regarding whether what has been called the eye-of-the-needle or anorthoscope phenomenon demonstrates “post-retinal storage” (Haber, 1968; Haber & Nathanson, 1968; Parks, 1965; Parks, 1968). In the original anorthoscope effect discussed earlier (and illustrated in Figure 1-15), the claim was made that people could “see” a stimulus pattern that was viewed through a slit in a screen that moved back and forth in front of the stimulus. As we already suggested, it seems that this sort of seeing is not altogether like the usual kind in that there is a memory load imposed by the task that shows up in differences in the ability to recover the shape depending on the order in which parts of the figure were presented. Haber & Nathanson raised the question of whether what is stored in the anorthoscope effect is an image, or whether it is more abstract information which allows an interpretation to be inferred (rather than seen). The question of when some episode constitutes a case of visual perception (i.e., of “seeing”), as opposed to being merely a case of drawing an inference from fragmentary visual cues, is more than a terminological one – it has implications for theories of visual memory and mental imagery.

An even more extreme case of the overly inclusive way in which the term “see” or “looks like” is used is provided by the case of “Doodles” – a type humorous visual puzzle or joke first developed by Roger Price, such as the ones in Figure 1-21 below. These have sometimes been cited (e.g., Hanson, 1958) to illustrate that what you see depends on what you know. (Look at each figures and then ask yourself: What does it look like? Then do it again after reading the captions in the footnote).

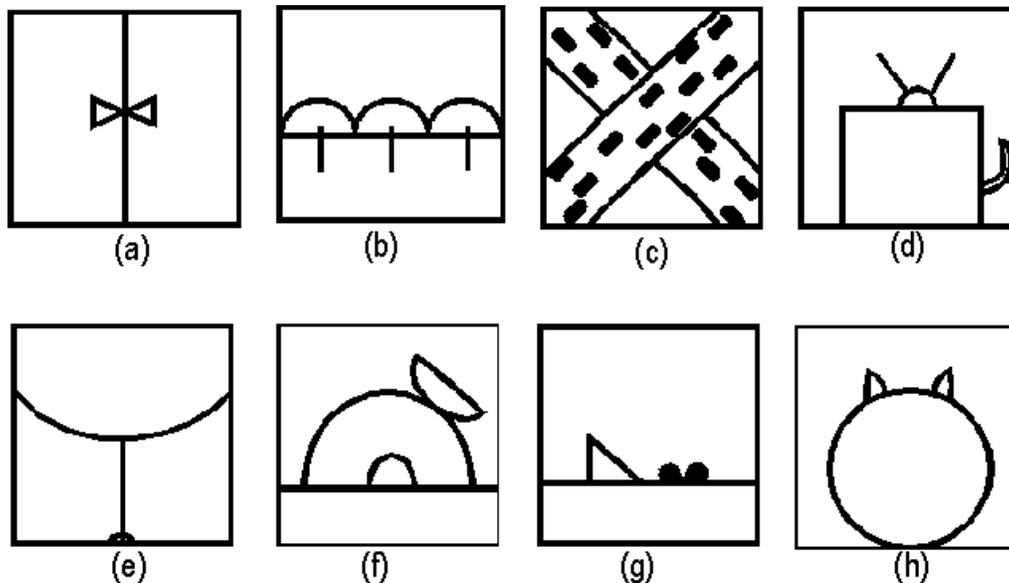


Figure 1-21: Sample “doodles”. What do you see? (see Footnote 9 for some answers)

Like Gestalt closure figures (or fragmented figures, discussed in Chapter 2 and illustrated in Figure 2-6 and Figure 2-7), these appear to come together suddenly to make a humorous closure.⁹ But unlike the fragmented figures, these interpretations clearly depend on collateral information. The question is: Do these cases illustrate the operation of the visual system, or are they more like puns or jokes in which the “punch line” causes one to cognitively reinterpret or reframe what came before (or what was seen).

Ordinary language uses terms like “appears” or “seems” in ways that do not distinguish plausible functions of the visual system from inferences based partly on visual cues and partly on other (nonvisual) information. For example we speak of someone “looking sick” or of a painting “looking like a Rembrandt”. Whatever the facts are about what is involved when some stimulus “looks like” a person with an illness or a painting by Rembrandt, it is at least plausible that such informal uses of these terms do not (nor are they intended to) “carve nature at her joints” the way that a scientific theory strives to.

1.4.7 Vision and conscious appearance: Can they be separated?

Although the intuitive sense of “how things look” provides the starting point in the study of visual phenomena, this is not the only way to determine what the visual system does or what it produces. For example, vision leads not only to the phenomenal experience of *seeing*, it also leads to our being able to act appropriately towards objects (e.g. point to them, grasp them, and so on). When certain properties are perceived, we can also often recognize them, make various judgments about them, show the capacity to discriminate them, or to perceive discontinuities between them when they are placed side-by-side (two properties of patches which, when placed side by side, are indistinguishable so that the patches appear to be continuous, are called “metamers”). In addition, under certain circumstances we can also show that they

⁹ Doodles (a) (b) and (c) are originals by Roger Price, the others are contributions to the Doodles home page maintained by Leo Valdes (<http://www.doodles.com>), reproduced with permission of Mr. Valdes. The original captions are:

- (a) Man wearing a bow tie entered a crowded elevator and the door closed on his tie.
- (b) Rear view of the starting line for a rat race.
- (c) Giraffes in love
- (d) Cat watching TV
- (e) Flea holding up an elephant
- (f) Igloo with a satellite dish.
- (g) Shark returning from a holiday at Disneyland
- (h) Rabbit blowing a large bubble.

lead to certain physiological responses (such as the galvanic skin response which is the basis of lie detector tests) or neurological responses, such as patterns of EEGs called event-related potentials, and so on. Another way to try to distinguish between purely visual phenomena and phenomena involving beliefs is to appeal to the interaction between two visual phenomena, one of which is independently known to occur in early vision. This is what was done in the interaction between “perceived virtual contours” and the Pogendorff illusion (Figure 1-5) and when we appealed to certain “signature properties” of vision, such as automatic figure-ground separation, interpretation in 3D, reversals, and apparent motion. We also hinted at other methods such as the use of Signal Detection Theory, Event-related potentials, Galvanic skin response. To understand whether certain phenomena are purely visual we can also appeal to existence of clinical cases of brain damage that show deficits in reports of visual perception and in the ability to recognize objects, but without concomitant deficits in related cognitive skills. For example there are remarkable cases of what is called “blind sight” (studied extensively by Weiskrantz, 1997) which occurs in some patients with cortical damage resulting in large blind regions in their visual field (often as large as half the visual field). When objects are held up before them in these “blind” regions, the patients say that they see nothing there. Yet when they are forced to guess or to reach for the objects (just to humor the experimenter) they perform significantly above chance in both types of tasks. This sort of report of not-seeing, accompanied by performance indicating visual information is being processed, also occurs with split-brain patients (patients who had their corpus callosum surgically cut in order to alleviate epileptic seizures, or who were born without the connecting fibers). In these patients there is almost no communication between the two hemispheres of the brain, so that the left half, which has the language skills, cannot communicate with right half, which gets input from the left half of each retina. Such people exhibit amazing symptoms (Gazzaniga, 2000). For example, they report that they do not see objects presented to the left half of their visual field. Yet their left hand (which is connected to the half of the cortex that is receiving visual information about the objects) is able to reach for the objects quite normally. In fact they can often recognize the objects by their feel or the sound they make when moved. Once the left hand brings the object into view of the right hemisphere, these people can report seeing them. Other related visual disorders also suggest that equating seeing with being able to report a conscious visual experience may be to unnecessarily limit the scope of the evidence for vision.

The point is that there is no limit to the type of evidence than can in principle be marshaled to help us understand visual perception. As we already remarked, even though perceptual experience may define the clear cases, the strategy in visual science, as in all human sciences, is then to let various convergent measures and the developing body of theory determine where the boundary between perception and cognition will fall. Thus there is no reason in principle why we should not include in the category of perception cases of unconscious perception. Indeed perhaps one might even have good reason to call certain mental states cases of unconscious perceptual *experiences*. None of these issues can be prejudged in the absence of at least a partial theory of what it is to have a conscious experience; once again common sense is no help in these matters. The everyday notion of seeing is too fluid and all-encompassing to be of scientific use. Science needs to make certain distinctions and to identify what (Simon, 1969) refers to as “partially decomposable” systems. But then such distinctions invariably defy the everyday prescientific ideas.

1.5 Where do we go from here?

This chapter has provided a sketch of some of the reasons why many people have assumed that vision provides us with an inner version of the world, more complete, detailed and extended, and more responsive to our beliefs, desires and expectations, than is the retinal information we are forced to deal with in the first instance. In the course of this discussion I have hinted that in formulating a scientific theory of vision we will more than likely have to shed much of our intuitively comfortable view, in particular we will have to jettison the phenomenal image or display and come to grips with the information-processing task that vision carries out. But we will also have to come to terms with other equally uncomfortable conceptual issues. For example, in the discussion so far we spoke freely about the *visual system* and the *visual process*. But what if there is no specifically visual process, but only an undifferentiated cognitive process. For example

many people view vision as being quite close in spirit to the process of science itself, where people use all the intellectual apparatus at their disposal to come up with theories which they then attempt to confirm or disconfirm, leading to newer (and hopefully better) theories and so on in an endless cycle. If that picture is correct than it is highly unlikely that there will ever be a theory of visual perception, any more than there is a theory of science. Indeed, the nature of the scientific process, or the problem of induction, remains one of the most difficult puzzles in philosophy. But we are here embarked on a more optimistic venture: We will defend the thesis that there is such a thing as a *visual system*, apart from the entire system of reasoning and cognizing of which humans and other organisms are capable. We will examine the claim that vision is, as Fodor puts it (Fodor, 1983), a *module*, informationally-encapsulated from the rest of cognition and operating with a set of autonomously specifiable principles. More particularly, I will argue that an important part of what we normally would call visual perception is *cognitively impenetrable*. Earlier I suggested that it is problematic to distinguish between vision and visual memory because space and time can be traded off in the visual process (as happens routinely when we scan our eyes around). What I now want to claim, in contrast, is that there *is* a distinction between “seeing” and “thinking”.

2. THE INDEPENDENCE OF VISION AND COGNITION¹⁰

2.1 Is Vision distinct from reasoning?

2.1.1 What determines what we see? Do we see what we expect to see?

If the first major seduction of our phenomenal experience is the belief that vision constructs an inner world or inner display, then the next one is that “seeing is believing”, or that there is little or no distinction between the visual system and the general reasoning system, other than that the former gets some of its initial information from the eyes. It is widely, if not universally, accepted that what we see is heavily conditioned by our beliefs and our expectations. The view that perception and cognition are continuous is particularly believable because it comports well with everyday experience as well as with the Zeitgeist – the spirit of the times – that celebrates the plasticity of the mind. The beginning of the second half of the 20th century was characterized by a belief in biologically limitless human potential. An advertisement on the American Public Television System declares, “If it can be imagined, it can be done: This is America!” In the debate between nature and nurture it was nature that had its day in the 1950s with the dominance of philosophical empiricism. That brought with it not only the view of the mind as a blank *tabula rasa*, upon which experience writes the entire adult intellectual capacity, but also the view that the newborn perceptual system provides the infant only with what William James called “A blooming buzzing confusion”. This picture of human nature has been thoroughly dismantled as new evidence shows ever more capacities in the newborn mind. One part of this prevalent ideology is a perceptual relativity: the view that how we perceive the world is conditioned by our beliefs, our culture, our moods and so on. The average person takes it for granted that how we see the world is radically influenced by our mental state; by our beliefs, our expectations, and our needs, hopes and fears, and above all, by our language and culture. And there are plenty of reasons to take this view. One of the more dramatic illustrations of this is magic, where the magician manipulates what we see by setting up certain false expectations. We are also told that when people are thirsty in a desert they often see oases. And who has not had the experienced of being afraid and then being “spooked” by harmless shadows which we mistake for signs of something awful. The popularity of what is known as the Sapir-Whorf hypothesis of linguistic relativity among the literate public (which gave us the apocryphal story that Eskimos have 17 different words for snow because their perceptual discrimination of types of snow is more refined – i.e., that they have 17 different ways of *seeing* snow) also supports this general view, as does the widespread belief in the cultural effect on our *ways of seeing* (e.g., the books by Carlos Castaneda). The remarkable placebo effect of drugs and of authoritative suggestions by people wearing white coats also bears witness to the startling malleability of perception, not to mention the effects of suggestions given under hypnosis.

In this chapter I will examine some of the reasons why this view has been generally held, not just by the public, but also by psychologists, and I will also examine some evidence against this view of vision. To anticipate the conclusion, what I will argue is that visual perception, in the everyday sense of the term, does indeed merge seamlessly with reasoning and other aspects of cognition. But the everyday sense of the term is too broad to be of scientific value precisely because it fails to make distinctions that “cut nature at her joints”. I will argue that within the broad category of what we call “vision” is an information processing system, which some have called “early vision”, that is highly complex, but which functions independently of what we believe. This system picks out or individuates objects in a scene and computes the spatial layout

¹⁰ Some of the material in this chapter, as well as in Chapter 3, is based in part on my paper, “Is vision continuous with cognition? The case for cognitive impenetrability of visual perception”, *Behavioral and Brain Science*, 22(3), 341-423, 1999. Additional technical arguments developed in that paper have been omitted here.

of visible surfaces and the 3D shape of the objects in the scene.¹¹ It thus covers a lot of what one means by visual perception. What it does not do is *identify* the things we are looking at, in the sense of relating them to things we have seen before, to the contents of our memory. And it does not make judgments about how things really are. In other words this aspect of vision is not the sole determiner of our perceptual beliefs – our beliefs about what we are seeing. In this sense then, seeing¹² is not the same as believing; far from it. Believing depends on all your wits and intelligence and knowledge of how the world works, whereas early vision does not. It depends on how the visual system was wired up by evolution as well as by biological, chemical and physical principles, and on the incoming patterns of light, but on little else. It would not be a great exaggeration to say that “early vision” – the part of visual processing that is prohibited from accessing general knowledge – computes just about everything that might be called a “visual appearance” of the world *except* the identities and names of the objects. This view, which I have referred to as the “independence thesis” or the “modularity of vision thesis,” flies in the face of a great deal of received wisdom, both in and out of visual science, and requires some elaboration. In particular, it requires drawing some conceptual distinctions and explaining a great deal of apparently contradictory evidence. By the time we are through with this topic we will have distinguished between seeing and believing, between “seeing” and “seeing as,” and between the processes carried out by visual system and pre-visual process of deciding where to focus attention or the post-visual process of deciding what the visual system reveals about the scene.

But first, let us look more closely at the basis for the belief in the relativity and plasticity of vision. The reasons for believing that vision and cognition are very closely linked go deeper than just our everyday experience. The view is backed by an enormous amount of experimental evidence from psychology and from social sciences more broadly (including cross-cultural observations). It is also supported by work in artificial intelligence that attempts to build computer systems that can recognize objects and scenes. Below I present some of this experimental evidence, which persuaded many scientists that vision is continuous with cognition. I do this in order to illustrate the reasons for the received wisdom, and also to set the stage for some critical distinctions and for some methodological considerations related to the interpretation generally placed on the evidence.

2.2 The case for the continuity of vision and cognition

2.2.1 The “New Look” in the psychology of perception

In 1947 Jerome Bruner published an extremely influential paper, called “*Value and need as organizing factors in perception*” (cited in Bruner, 1957). This paper presented evidence for what was then a fairly radical view; that values and needs determine how we perceive the world, down to the lowest levels of the visual system. As Bruner himself relates it in a later review paper (Bruner, 1957), the Value and needs essay caught on beyond expectations, inspiring about 300 experiments in the following decade, all of which showed that perception was infected through and through by perceivers’ beliefs about the world and about

¹¹ Notice that it is critical for our thesis that the notion of early vision include, among other things, such functions as the individuation of objects (which will be the topic of Chapter 5), as well as the computation of what are referred to as “surface layouts” – the shape of the visible surfaces in our field of view. If it were not for the fact that early vision includes such complex features of the visible world, the independence theses would be trivial since everyone believes that *something* is detected by the visual system without regard for beliefs and expectations, otherwise we would only see whatever we wished! The more conventional view (e.g., that was held by empiricists and perhaps by “New Look” theorists discussed in section 2.2.1) is that the only thing that is isolated from cognition is the operation of the sensors. We will return to the question of the nature of the output of early vision in the next chapter.

¹² Having made the distinction between the ordinary sense of vision and what I called “early vision” I will often fall into the habit of referring to the latter as “vision” and of this process as resulting in “seeing”. I do this because the narrow technical sense of “vision” is precisely that part of visual perception that is unique to, and therefore constitutive of, visual perception. The broader sense is simply a confounding of several distinct processes. The policy of referring to the part of a process that forms the unique core of that process by the more general term is precisely what Chomsky does when he uses the term “language” to refer to that part of our entire linguistic ability that is unique to language, even though understanding and generating linguistic signs clearly involves all of our cognitive faculties (Chomsky, 1976).

the particular scene before them: hungry people were more likely to see food and to read food-related words, poor children systematically overestimate the size of coins relative to richer children, and anomalous or unexpected stimuli tend to be assimilated to their regular or expected counterparts.

Bruner's influential theory formed the basis of what became known as the "New Look in Perception," a movement that flourished in the 1960s and 1970s and continues to be influential even today in many areas of social science. According to this view, we perceive in conceptual categories. There is no such thing as a "raw" appearance or an "innocent eye": we see something *as* a chair or a table or a face or a particular person, and so on. As Bruner put it, "...all perceptual experience is necessarily the end product of a categorization process" and therefore "perception is a process of categorization in which organisms move inferentially from cues to category identity and ... in many cases, as Helmholtz long ago suggested, the process is a silent one." Perception, according to Bruner, is characterized by two essential properties: it is categorical and it is inferential. Thus perception might be thought of as a form of problem solving in which part of the input happens to come in through the senses and part through needs, expectations, and beliefs, and in which the output is the category of the object being perceived. Because of this there is no essential distinction between the processes of perception and thought.¹³

This view opposed the earlier position that had been adopted by psychologists from as wide a perspective as structuralists (like Titchener, 1915), Gestaltists (like Wallach, 1976) and even the early work of James J. Gibson (Gibson, 1966). Adherents of all these schools had accepted some sort of distinction between a pure stimulus event and a stimulus event that had interacted with past experience, or as it was sometimes put, between the "visual field" and the "visual world", or between perception and conception (or, as the latter was sometimes called, *apperception* – the process of assimilating perception into one's cognitive world). It would not be a misstatement to say that these thinkers accepted that there is a difference between appearances and beliefs, even though they would not have put it in those terms.

The New Look fit well with the *Zeitgeist*, which saw the organism as highly malleable by its environment, both in the short term and in the longer term (in the latter case this malleability was called 'learning'). It was also a reaction against sense-data views of perception, views that had attained some currency with the structuralist and introspectionist schools of perception. Sense-data theories assumed that percepts were constructed out of more basic elements of experience called "sensations". Sensations were different in kind from percepts; they were not perceptual categories but the raw material of the senses. This version of perceptual atomism lost much of its popularity with the fall of the introspective method, as well as with the general disenchantment with perceptual atomism promoted by Gestalt psychology. It seemed that basic perceptual atoms, especially ones that could be consciously sensed, were not to be had; perception was, as the Gestalt psychologists would say, always greater than the sum of its more elementary parts. In this spirit, the field was ripe for a holistic all-encompassing theory of perception that integrated it into the general arena of induction and reasoning.

There were literally thousands of experiments performed from the 1950s through the present time showing that the perception of almost any pattern, from the perception of sentences in noise to the recognition of familiar stimuli at short exposures, could be influenced by observers' knowledge and expectations. Bruner cites evidence as far-ranging as findings from basic psychophysics to psycholinguistics and high level perception – including social perception. For example, Bruner cited evidence that magnitude estimation is sensitive to the response categories with which observers are provided, as well as the anchor points and adaptation levels induced by the set of stimuli, from which he concluded that cognitive context affects such simple psychophysical tasks as magnitude judgments. In the case of more complex patterns there is even more evidence for the effects of what Bruner calls "readiness" on perception. The recognition threshold for words decreases as the words become more familiar (Soloman & Postman, 1952). The

¹³ (Bruner, 1957) characterized his claim as a "bold assumption" and was careful to avoid claiming that perception and thought were "utterly indistinguishable". In particular he explicitly recognized that perception "appear(s) to be notably less docile or reversible" than "conceptual inference." This lack of "docility" will, in fact, play a central role in the present argument for the distinction between perception and cognition.

exposure time required to report a string of letters shown in the flash-exposure instrument known as the tachistoscope, which was becoming extremely popular in psychology laboratories at that time, varies with the predictability of the string (Miller, Bruner & Postman, 1954): random strings (such as YRULPZOC) require a longer exposure for recognition than strings whose sequential statistics approximate those of English text (such as VERNALIT, which is a non-word string constructed by sampling 4-letter strings from a corpus of English text); the higher the order of approximation, the shorter the exposure required for recognition. The level of background noise at which listeners can still recognize a word is higher if that word is part of a sentence (where it could be predicted more easily) or even if it occurs in a list of words whose order statistically approximates English (Miller, 1962). More generally, words in sentences can be recognized more easily and in more adverse conditions than can words alone or in random lists.

Similar results were found in the case of nonlinguistic stimuli. For example, the exposure duration required to correctly recognize an anomalous playing card (e.g., a black ace of hearts) is higher than the time required to recognize a normal card (Bruner & Postman, 1949). Also, as in the letter and word recognition cases, the perceptual thresholds reflect the likelihood of occurrence of the stimuli in a particular context, and even their significance to the observer (the latter being illustrated by studies of so-called “perceptual defense”, in which pictures previously associated with shock, show elevated recognition thresholds). The reconstruction of partially-occluded figures was also taken as showing that vision makes use of knowledge in order to restore familiar shapes, as in the “New York” example in Chapter 1, Figure 1-4.

The results of these experiments were explained in terms of the accessibility of perceptual categories and the hypothesize-and-test nature of perception (where the “hypotheses” can come from any source, including immediate context, memory and general knowledge). There were also experiments that investigated the hypothesize-and-test view more directly. One way this was done was by manipulating the “availability” of perceptual hypotheses. For example, (Bruner & Minturn, 1955) manipulated what they called the “readiness” of the hypothesis that stimuli were numbers as opposed to being letters (by varying the context in which the experiment was run), and found that ambiguous number-letter patterns (e.g., a “B” with gaps so that it could equally be a “13”) were reported more often as congruous with the preset hypothesis. Also if a subject settles on a false perceptual hypothesis in impoverished conditions (e.g., with an unfocused picture), then the perception of the same stimulus is impaired, so it takes longer or requires a better display before a figure is correctly recognized when it is first presented unfocused. When subjects make incorrect guesses as the focus is gradually improved, they eventually perform worse compared with when a false hypothesis is not made (Bruner & Potter, 1964; Wyatt & Pola, 1979).

Because of these and other types of experiments showing contextual effects in perception, the belief that perception is thoroughly contaminated by such cognitive factors as expectations, judgments, beliefs and so on, became the received wisdom in much of psychology, with virtually all contemporary elementary texts in human information processing and vision taking that point of view for granted (Lindsay & Norman, 1977; Sekuler & Blake, 1994). The continuity view also became widespread within philosophy of science. Thomas Kuhn (Kuhn, 1972) gathered a cult following with his view of scientific revolutions, in which theory change was seen as guided more by social considerations than by new data. The explanation was that theoretical notions in different theories are essentially incommensurable and so evidence itself is contaminated by the theoretical systems within which scientists worked. Philosophers of science like (Feyerabend, 1962) and (Hanson, 1958) argued that there was no such thing as objective observation since every observation was what they called “theory laden”. These scholars frequently cited the New Look experiments showing cognitive influences on perception to support their views. Mid-nineteenth-century philosophy of science welcomed the new holistic all-encompassing view of perception that integrated it into the general framework of induction and reasoning.

2.2.2 The perspective of neuroscience

During the heyday of the New Look (in the 1960s and the 1970s), speculative neuropsychology such as the influential work of the influential Canadian psychologist Donald Hebb, was in general sympathy with the interactionist view (see Hebb, 1949). However, the important discovery of single-cell receptive fields and

the hierarchy of simple, complex, and hypercomplex cells (Hubel, 1962) gave rise to the opposing idea that perception involves a hierarchical process in which larger and more complex aggregates are constructed from more elementary features. In fact, the hierarchical organization of the early visual pathways sometimes encouraged an extreme hierarchical view of visual processing, in which the recognition of familiar objects by master cells was assumed to follow from a succession of categorizations by cells lower in the hierarchy. This idea seems to have been implicit in some neuroscience theorizing, even when it was not explicitly endorsed. Of course such an assumption is not warranted by the mere existence of cells that responded to more and more abstract properties, since any number of processes, including inference, could in fact intervene between the sensors and the high-level pattern-neurons.

There were some early attempts to show that some top-down or centripetal influences (i.e., from higher brain regions to sensors) also occurred in the nervous system. For example, (Hernandez-Péon, Scherrer & Jouvet, 1956), showed that the auditory response in a cat's cochlear nucleus (the first neural way-station from the ear) was attenuated when the cat was paying attention to some interesting visual stimulus. More recently, the notion of *focal attention* has begun to play a more important role in behavioral neuroscience theorizing and some evidence has been obtained showing that the activity of early parts of the visual system can indeed be influenced by selective attention (e.g., Haenny & Schiller, 1988; Moran & Desimone, 1985; Mountcastle, Motter, Steinmetz, & Sestokas, 1987; Sillito, Jones, Gerstein, & West, 1994; van Essen & Anderson, 1990). There is even recent evidence that attention can have long-term effects as well as transitory ones (Desimone, 1996). Some writers (e.g., Churchland, 1988) have argued that the presence of outgoing (centripetal) nerve fibers running from higher cortical centers to the visual cortex constitutes *prima facie* evidence that vision must be susceptible to cognitive influences. However, the role of the centripetal fibers remains unknown except where it has been shown that they are concerned with the allocation of attention. I will argue later that allocation of *focal attention* is indeed a principal means by which top-down effects can occur in vision, but that these do not constitute cognitive penetration.

What the evidence shows is that attention can selectively sensitize or gate certain regions of the visual field as well as certain stimulus properties. Even if such effects ultimately originate from "higher" centers, they constitute one of the forms of influence that I claim is prior to the operation of early vision – in particular, they constitute an attentional selection of relevant properties. By and large the neuroscience community (at least since the influential work of neuro-computationalist, David Marr) is now interested in how the visual system decomposes into separate modules and is comfortable with the idea that vision itself is far less dependent on cognition than assumed by the more behavioral psychologists of the same era. I will look at some of the evidence that is considered relevant to this newer perspective in section 2.3 below.

2.2.3 The perspective of *robot vision*

Another line of support for the idea that vision implicates reasoning and memory comes from the field of artificial intelligence, or computer vision, where the goal has been to design systems that can "see" or exhibit visual capacities of some specified type. The approach of trying to design systems (i.e., robots) that can see well enough to identify objects or to navigate through an unknown environment using visual information, has the virtue of at least setting a clear problem to be solved. In computer vision the goal is to design a system that is *sufficient* to the task of exhibiting properties we associate with visual perception. The sufficiency condition on a theory is an extremely useful constraint, since it forces one to consider possible mechanisms that could accomplish certain parts of the task. Thus it behooves the vision researcher to consider the problems that computer vision designers have run into, as well as to some of the proposed solutions that have been explored. And indeed, modern vision researchers have paid close attention to work on computer vision and vice versa. Consequently it is not too surprising that the history of computer vision closely parallels the history of ideas concerning human vision.

Apart from some reasonably successful early "model-based" vision systems capable of recognizing simple polyhedral (block-shaped) objects, when the scene was restricted to only such objects (Roberts, 1965), most early approaches to computer vision were of the data-driven or so-called "bottom-up" variety. They took elementary optical features as their starting point and attempted to build more complex

aggregates, leading eventually to the categorization of the pattern. Many of these hierarchical models were statistical pattern-recognition systems inspired by ideas from biology, including Rosenblatt's Perceptron (Rosenblatt, 1959), Uttley's Conditional Probability Computer (Uttley, 1959), and Selfridge's Pandemonium (Selfridge, 1959).

In the 1960s and 1970s a great deal of the research effort in computer vision went into the development of various "edge-finding" schemes in order to extract reliable features to use as a starting point for object recognition and scene analysis (Clowes, 1971). Despite this effort, the edge-finders were not nearly as successful as they needed to be if they were to serve as the primary inputs to subsequent analysis and identification stages. The problem is that if a uniform intensity-gradient threshold is used as a criterion for the existence of edges in the image, it invariably results in one of two undesirable situations. If the threshold is set low it leads to the extraction of a large number of features that corresponded to shadows, lighting and reflectance variations, noise, or other luminance differences unrelated to the existence of real edges in the scene. On the other hand, if the threshold is set higher, then many real scene edges that are clearly perceptible by human vision are missed. This dilemma led to attempts to guide the edge finders into more promising image locations or to vary the edge-threshold depending on whether an edge was more likely at those locations than at other places in the image.

The idea of guiding local edge-finding operators using knowledge of the scene domain may have marked the beginning of attempts to design what are known as knowledge-based vision systems. At MIT the slogan "heterarchy, not hierarchy" (Winston, 1974) was coined to highlight the view that there had to be context-dependent influences from domain knowledge, in addition to local image features such as intensity discontinuities. Guided line-finders were designed (e.g., Kelly, 1971; Shirai, 1975) based on this approach. The idea that knowledge is needed at every level in order to recognize objects was strongly endorsed by (Freuder, 1986) in his proposal for a system that would use a great deal of specialized knowledge about certain objects (e.g., a hammer) in order to recognize these objects in a scene. Riseman and Hanson also took a strong position on this issue, claiming, "It appears that human vision is fundamentally organized to exploit the use of contextual knowledge and expectations in the organization of visual primitives ... Thus the inclusion of knowledge-driven processes at some level in the image interpretation task, where there is still a great degree of ambiguity in the organization of the visual primitives, appears inevitable" (Riseman & Hanson, 1987, p 286)). Indeed a rather heated debate ensued between supporters of the bottom-up view (Clowes, 1971) that utilized line-finders in the initial stage of processing, and those who believed that vision systems would have to be heavily knowledge-based all the way down (Michie, 1986).

The knowledge-based approach is generally conceded to be essential for developing high performance computer vision systems using current technology. Indeed, virtually all currently successful automatic vision systems for robotics or for such applications as analyzing medical images or automated manufacturing, are model-based (e.g., Grimson, 1990) – i.e., their analysis of images is guided by some stored model of possible objects that could occur in the input scene. Although model-based systems may not use general knowledge and draw inferences, they fall in the knowledge-based category because they quite explicitly use knowledge about particular objects in deciding whether a scene contains instances of that object.¹⁴ In addition, it is widely held that the larger the domain over which the vision system must operate, the less likely that a single type of stored information will allow reliable recognition. This is because in the general case, the incoming data are too voluminous, noisy, incomplete, and intrinsically ambiguous to allow univocal analysis. Consequently, so the argument goes, a computer vision system must make use of many different domain "experts", or sources of knowledge concerning various levels of organization and different aspects of the input domain, from knowledge of optics to knowledge of the most likely properties to be found in the particular domain being visually examined.

¹⁴ An alternative, that is sometimes also referred to as a "model based" approach, that uses some form of "general purpose" model of objects (Lowe, 1987; Zucker, Rosenfeld & David, 1975) — or even of parts of such object (Biederman, 1987) — does not fall into this category because the models are not selected on the basis of expectations about the particular situation being observed (where the latter depends on what the observer knows and believes). This type of constrained perception falls into the category of "natural constraint" approaches that will be discussed in section Chapter 3.

The knowledge-based approach has also been exploited in a variety of speech-recognition systems. For example, the early speech recognition systems developed at BBN (Woods, 1978) (known as SPEECHLIS or HWIM, for “Hear What I Mean”) is strongly knowledge-based. Woods has argued for the generality of this approach and has suggested that it is equally appropriate in the case of vision. Two other speech recognition systems developed at Carnegie-Mellon university, including HEARSAY (described by Reddy, 1975), and Harpy, (described by Newell, 1980a), also use multiple sources of knowledge and introduced a general scheme for bringing knowledge to bear in the recognition process. These speech recognition systems use a so-called “blackboard architecture” in which a common working memory is shared by a number of “expert” processes, each of which contributes a certain kind of knowledge to the perceptual analysis. Each knowledge source contributes “hypotheses” as to the correct identification of the speech signal, based on its area of expertise. Thus, for example, the acoustical expert, the phonetic expert, the syntactic expert, the semantic expert (which knows about the subject matter of the speech), and the pragmatic expert (which knows about discourse conventions) each propose the most likely interpretation of a certain fragment of the input signal. The final analysis is a matter of negotiation among these experts. What is important here is the assumption that the architecture (the relatively fixed structural properties of the system) permits any relevant source of knowledge to contribute to the recognition process at every stage. This general scheme has also been used as the basis for vision systems such as those developed by (Freuder, 1986; Riseman & Hanson, 1987). Figure 2-1 below shows the structure of such a system (showing both speech and vision experts) illustrating how each expert can have an input at any stage in the analysis, providing a completely open system.

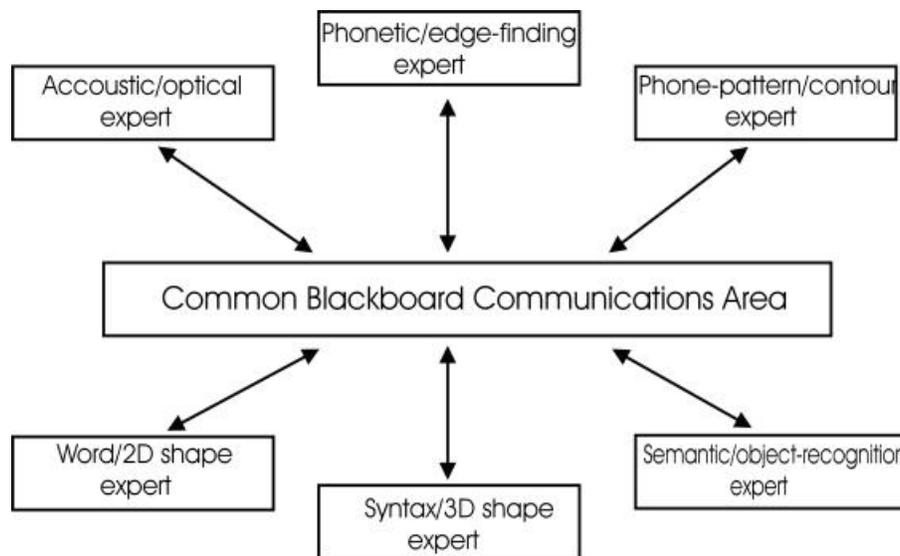


Figure 2-1: Sketch of the “blackboard architecture” used by the HEARSAY speech understanding system, as well as by some computer vision systems.

The idea of complete freedom of communication among different “experts” (through the common “blackboard”) received wide recognition in many areas of psychology and artificial intelligence. In fact it was for a time the received wisdom for how such pattern recognizers as systems for reading text might be organized. A popular idea, very closely related to the blackboard architecture, was based fairly directly on Selfridge’s Pandemonium idea, in which various experts competed for the attention of an executive decision maker, as illustrated in Figure 2-2 in a popular text on human information processing (Lindsay & Norman, 1977).

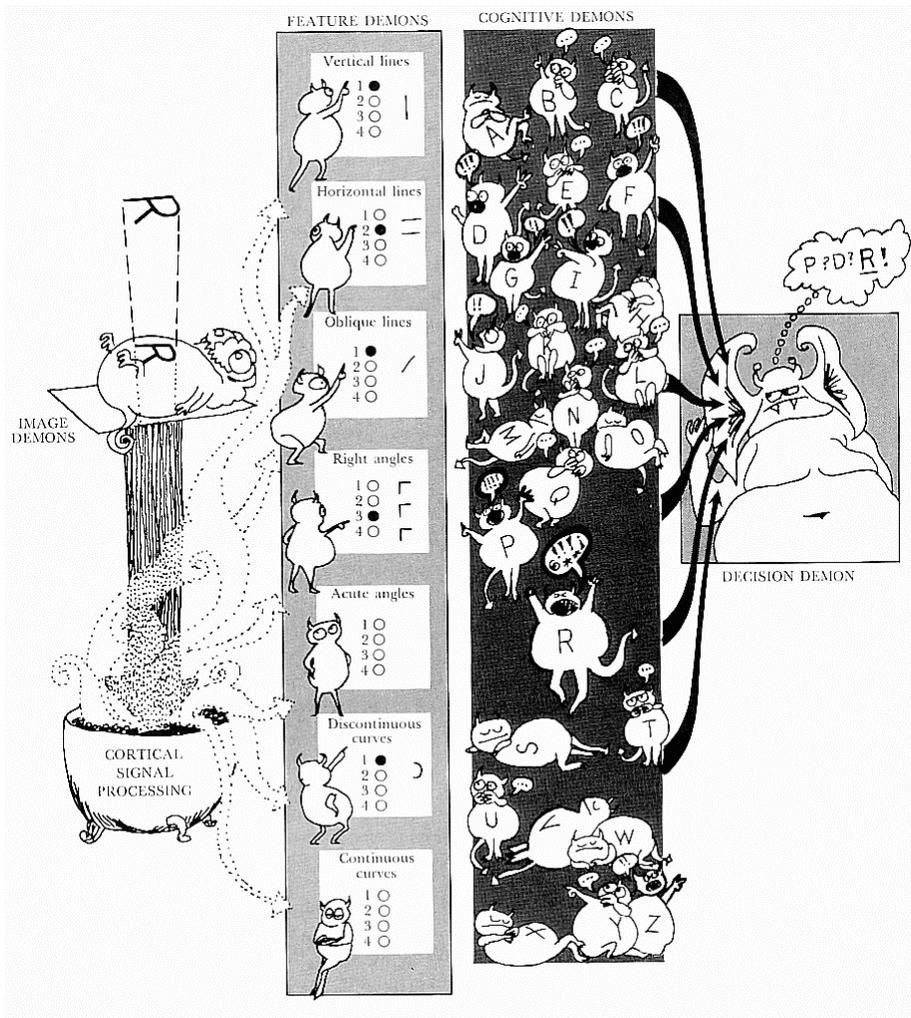


Figure 2-2. A caricature of the “Pandemonium” style of processing in which “demons” specializing in various aspects of the recognition problem vie for recognition by a master “decision demon”. In this case the idea is applied to the problem of word recognition in a system for reading text (from Lindsay & Norman, 1977).

While it is true that computational systems that make use of knowledge do better than ones that do not, I will argue later that one needs to distinguish between systems that access and use knowledge, such as those just mentioned, and systems that have constraints on interpretation built into them that reflect certain properties of the world. The latter embody an important form of “visual intelligence” that is perfectly compatible with the independence thesis and will be discussed in Chapter 3.

2.2.4 Seeing and knowing: Where do we stand?

Both the experimental and informal psychological evidence in favor of the idea that vision involves the entire cognitive system appears to be so ubiquitous that you might wonder how anyone could possibly believe that vision is separate and distinct from cognition. The answer, I claim, lies not in denying the evidence that shows the importance of knowledge for visual apprehension (although in some cases we will need to reconsider the evidence itself), but in making certain distinctions. It is clear that what we believe about the world we are looking at does depend on what we know and expect. In that sense we can easily be deceived—as in magic tricks. But as noted earlier, seeing is not the same as believing, the old adage notwithstanding. In order to understand visual perception it is essential to distinguish certain stages in the process, in particular a stage – which I call *early vision* (after David Marr and other vision scientists) – that

is prohibited from accessing relevant knowledge of the world or of the particular scene – and other stages that are permitted, or in some cases are even required by the nature of the task (e.g., recognizing a familiar face) to access such knowledge. The knowledge-dependent (or cognitively penetrable) stages include a *pre-perceptual stage*, wherein vision is directed at relevant places or objects in a scene, and a *post-perceptual stage*, in which memory is accessed and judgments are made about what is in the scene. The idea of drawing a sharp distinction between parts of visual perception and cognition, or between stages of visual perception has been anathema to much of psychology and contemporary scholarship in general, although (Fodor, 1983) has done much to revive its popularity. In what follows I will suggest some reasons why such a distinction is empirically justified.

2.3 Some reasons for questioning the continuity thesis

Before getting into the details of some methodological and experimental findings supporting the thesis that a major part of the visual process is cognitively impenetrable, I provide a brief summary of why I believe this to be the case despite the sorts of evidence already sketched. Here are four general reasons why it makes sense to consider the possibility that there is a principled demarcation between early vision and cognition.

2.3.1 Evidence of the cognitive impenetrability of illusions

As Bruner himself noted (see note 13): perception appears to be rather resistant to rational influence. It is a remarkable fact about the perceptual illusions that knowing about them does not make them disappear: Even after you have had a good look at the Ames room—perhaps even built it yourself—it still looks as though the person on one side is much bigger than the one the other side (Ittelson & Ames, 1968). Knowing that you measured two lines to be exactly equal does not make them look equal when arrowheads are added to them to form the Müller-Lyer illusion, or when a background of converging perspective lines are added to form the Ponzo illusion, as shown in Figure 2-3.

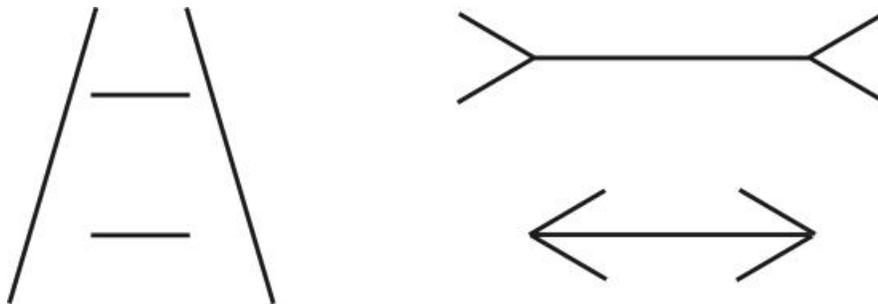


Figure 2-3. Illustrations of the Ponzo illusion (on the left) and the Müller-Lyer illusion (on the right). In both cases the horizontal lines above one another are the same length.

For another example in which the visual system's internal mechanisms override your knowledge, consider the blocks in Figure 2-4. Which of the top faces of blocks, A or C, is identical in size and shape (except for being rotated) to face B? If you check using a ruler or by cutting the figures out of paper you will find that the face labeled A is identical to the face labeled B while C is quite different. Notice that such illusions are not just stubborn, in the way some people appear unwilling to change their minds in the face of contrary evidence: it is simply impossible to make something look to you the way you know it really is. What is noteworthy is not that there are perceptual illusions; it is that in these cases there is a very clear separation between what you see and what you know is actually there – what you believe. What you believe depends upon how knowledgeable you are, what other sources of information you have, what your utilities are (what's important to you at the moment), how motivated you are to figure out how you might have been misled, and so on. Yet how things look to you appears to be impervious to any such factors, even when what you know is both relevant to what you are looking at and at variance with how you see it. Later in

section 2.5 I will examine (and reject) claims that certain kinds of illusions (e.g. reversals of ambiguous figures and perceptual closure of difficult percepts) are susceptible to cognitive influences.

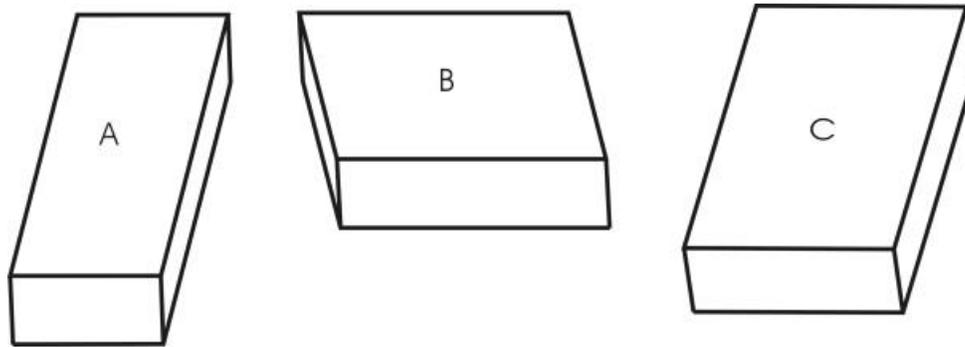


Figure 2-4. Which of these figures has the same top face as B (A or C)? (after Shepard, 1981).

2.3.2 Evidence of the independence of principles of visual organization and of inference

There are many regularities within visual perception – some of them highly complex and subtle – that are automatic, depend only on the visual input, and often follow principles that appear to be quite different from the principles of rational reasoning. These principles of perception differ from the principles of inference in two ways.

(1) First, unlike the principles of inference, perceptual principles are responsive only to visually presented information. One way to think of the difference between visual representations and thoughts is to think of the representations that occur within the visual system as being in a proprietary vocabulary, distinct from the vocabulary that occurs in representations of thoughts and beliefs. This vocabulary encodes such perceived properties as which regions of a scene go together as a single object, which contours go with which surfaces, which surfaces partially occlude other surfaces, and so on. Perceptual principles specify how certain encoded properties (or “scene labels”) go with other encoded properties. In computer vision a major part of early vision is concerned with what is called *scene labeling* or *label-propagation* (Chakravarty, 1979; Rosenfeld, Hummel & Zucker, 1976), wherein principles of label-consistency are applied to represented features in a scene in order to compute the correct labeling (we will see examples of this sort of labeling in the next chapter, section 3.1.1.1). Principles of visual interpretation explain why it is that the way you perceive some aspect of a visual scene determines the way you perceive another aspect of the scene. When a percept of an ambiguous figure (like a Necker Cube) reverses, a variety of properties (such as the perceived relative size and luminance of the faces) appear to automatically change together to maintain a coherent percept, even if it means a percept of an impossible 3-D object, as in Escher drawings. Such intra-visual regularities have been referred to as “perceptual couplings” (Epstein, 1982; Rock, 1997). (Gogel, 1997/1973) attempted to capture some of these regularities in what he called *perceptual equations*. Such equations provide no role for what the perceiver knows or expects because the perception of visual form is *not* sensitive to the beliefs that perceivers have about what the scene being examined *should* look like, given what they know about the circumstances of that scene. The question of why certain principles (or equations) should be embodied in our visual systems is one that can only be answered by examining the function that vision has served in allowing organisms to survive in our kind of world. The particular equations or couplings may be understood in relation to the organism’s needs and the nature of world it typically inhabits (see Chapter 3 for a discussion of perceptual coupling). A more extensive discussion of the notion of *natural constraints* is provided in section 3.1.1).

(2) Second, the principles of visual organization are quite different from those of logical inference and often do not appear to conform to what might be thought of as tenets of “rationality”. Particularly revealing examples of the difference between the organizing principles of vision and the principles of inference are to be found in the phenomenon of “amodal completion”. This phenomenon, first studied by Michotte, refers

to the fact that partially occluded figures are not perceived as the fragments of figures that are actually in view, but as whole figures that are partially hidden from view behind the occluder (a distinction which is phenomenally quite striking). It is as though the visual system “completes” the missing part of the figure and the completed portion, though it is constructed by the mind, has real perceptual consequences (see Figure 1-6). Yet the form taken by an amodal completion (the shape that is “completed” or amodally perceived to be behind the occluder) follows complex principles of its own – which are generally not rational principles, such as semantic coherence or even something like maximum likelihood. As (Kanizsa, 1985; Kanizsa & Gerbino, 1982) have persuasively argued, these principles do not appear to reflect a tendency for the simplest description of the world and they are insensitive to knowledge and expectations, and even to the effects of learning (Kanizsa, 1969). For example, Figure 2-5 shows a case of amodal completion in which the visual system constructs a complex and asymmetrical completed shape rather than the simple octagon, despite the presence of the adjacent examples. In this and very many other such examples (many are discussed by Kanizsa in the papers cited) the *simplest* figure is not the one chosen, but rather one that conforms to some special principle that applies to local regions of the image. It is precisely because of this that there are visual illusions; the visual system *cannot* ignore its wired-in geometrical principles in favor of what the perceiver knows to be true.¹⁵

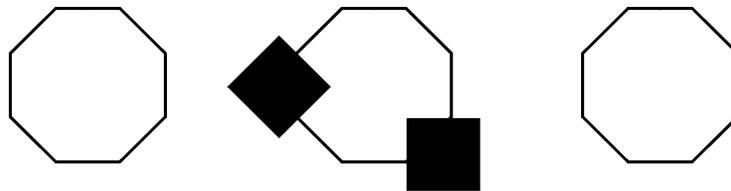


Figure 2-5: Kanizsa “amodal completion” figure. The completion preferred by the visual system is not the simplest figure despite the flanking examples of such figures. (After Kanizsa, 1985).

2.3.3 Neuroscience evidence for top-down attenuation and gating of visual signals

In section 2.2.2 I mentioned the existence of top-down neural pathways in vision. I also pointed out that the primary function of these pathways appears to be to allow attention to selectively sensitize or gate certain objects or regions of the visual field, as well as certain physical properties of the stimuli. Even if such effects ultimately originate from “higher” centers, they constitute one of the forms of influence that I claimed was prior to the operation of early vision – i.e., they constitute an early attentional selection of relevant properties.

Where both neurophysiological and psychophysical data show top-down effects, they do so most clearly in cases where the modulating signal originates *within* the visual system itself (roughly identified with the visual cortex, as mapped out, say, by Felleman & Van Essen, 1991). There are two major forms of modulation, however, that appear to originate from outside the visual system. The first is one to which I have already alluded – modulation associated with focal attention, which can originate either from events in the world which attract attention automatically (exogenous control) or from voluntary cognitive sources (endogenous control). The second form of extra-visual effect is the modulation of certain cortical cells by signals originating in both visual and motor systems. A large proportion of the cells in posterior parietal cortex (and in what Ungerleider & Mishkin, 1982, identified as the dorsal stream of the visual or visuomotor pathway) are activated jointly by specific visual patterns together with specific behaviors carried out (or

¹⁵ Of course if the principles by which vision constructs a representation of the world were totally capricious we would find ourselves walking into walls and generally not faring well in our commerce with the world, so the principles must be ones that more often than not yield a true description of the world in typical situations, even if they do not do it by rational inferential means, but by virtue of local geometrical principles. We will have occasion to return to this point (in Chapter 3), referred to as the tendency of the visual system to embody *natural constraints*, since this is an important general principle which explains why vision, which is insensitive to knowledge and processes of rational inference, nevertheless manages to solve visual problems mostly the way they need to be solved for the purposes of survival.

anticipated) that are related to these visual patterns; see the extensive discussion in (Milner & Goodale, 1995), as well as the review in (Lynch, 1980). There is now a great deal of evidence suggesting that the dorsal system is specialized for what (Milner & Goodale, 1995) call “vision for action”. What has not been reported, to my knowledge, is comparable evidence to suggest that cells in any part of the visual system (and particularly the ventral stream that appears to be specialized for recognition) can be modulated in a similar way by higher level cognitive influences. While there are cells that respond to such highly complex patterns as a face, and some of these may even be viewpoint-independent (i.e., object-centered) (Perrett, Mistlin & Chitty, 1987), there is no evidence that such cells are modulated by nonvisual information about the identity of the face (e.g. whether it was the face expected in a certain situation). More general activation of the visual system by voluntary cognitive activity has been demonstrated by PET and fMRI studies (Kosslyn, 1994), but no content-specific modulations of patterns of activity by cognition have been shown (i.e., there is no evidence for patterns of activity particular to certain *interpretations* of visual inputs), as they have in the case of motor-system modulation (I will take up this topic again in Chapter 7).

It is not the visual complexity of the class to which the cell responds, nor whether the cell is modulated in a top-down manner that is at issue, but whether or not the cell responds to how a visual pattern is *interpreted*, where the latter depends on what the organism knows or expects. If vision were cognitively penetrable, one might expect there to be cells that respond to certain interpretation-specific perceptions. In that case whether or not the cell responds to a certain visual pattern would appear to be governed by the cognitive system in a way that reflects how the pattern is conceptualized or understood.¹⁶ Studies of Macaque monkeys by Perrett and his colleagues suggest that cells in the temporal cortex respond only to the *visual* character of the stimulus and not to its cognitively-determined (or conceptual) interpretation. For example, (Perrett, Harries, Benson, Chitty, & Mistlin, 1990) describe cells that fire to the visual event of an experimenter “leaving the room” – and not to comparable experimenter movements that are not directed towards the door. Such cells clearly encode a complex class of events (perhaps involving the relational property “towards the door”), which the authors refer to as a “goal centered” encoding. However they found no cells whose firing was modulated by what they call the “significance” of the event. The cells appear to fire equally no matter what the event means to the monkey. As Perrett et al., put it (p195), “The particular significance of long-term disappearance of an experimenter ... varies with the circumstances. Usually leaving is of no consequence, but sometimes leaving may provoke disappointment and isolation calls, other times it provokes threats. It would ... appear that [for the firing of certain cells] it is the visual event of leaving the laboratory that is important, rather than any emotional or behavioral response. In general, cells in the temporal cortex appear to code visual objects and events independent of emotional consequences and the resulting behavior.” Put in terms of the present thesis, I would say that although what such cells encode may be complex, it is not sensitive to the cognitive context.

2.3.4 Evidence of dissociation of visual and cognitive functions in the brain

One intriguing source of evidence that vision can be separated from cognition comes from the study of pathologies of brain function that demonstrate dissociations among various aspects of vision and cognition. Even when, as frequently happens, no clear lesion can be identified, the pattern of deficits can provide evidence of certain dissociations and co-occurrence patterns of skill. They thus constitute at least initial evidence for the taxonomy of cognitive skills. The discovery that particular skill components can be

¹⁶ Changes in attenuation/sensitivity can result in different percepts. Whether or not this constitutes cognitive penetration depends on two things: (a) what kinds of perceptual changes can be underwritten by changing activation levels and (b) whether the particular changes can be attributed to appropriate differences in the contents of beliefs and expectations. As for (a) it is dubious that the sort of influence that allows people to see a word whose meaning is predicted from the context, to see monsters when they are afraid or to see food when they are hungry (as claimed by the New Look school) can be supported by differences in attenuation or sensitivity (see the discussion of this issue in Chapter 4). But (b) is even more germane because it matters whether or not the influence comes from within the visual system or from outside. We know that how you interpret a certain portion of an image depends on how you interpret other parts of the image. Such intra-visual effects do not constitute cognitive penetration. Unfortunately, the neuroanatomical data do not cast light on that question.

dissociated from other skill components (particularly if there is evidence of a double-dissociation in which each component occurs without the other), provides a *prima facie* reason to believe that these skills might constitute independent systems.

Consider the example of visual agnosia, a rather rare family of visual dysfunctions, in which a patient is often unable to recognize formerly familiar objects or patterns. In these cases (many of which are reviewed in Farah, 1990) there is typically no impairment in sensory, intellectual or naming abilities. A remarkable case of classical visual agnosia is described in a book by Glyn Humphreys and Jane Riddoch (Humphreys & Riddoch, 1987). After suffering a stroke that resulted in bilateral damage to his occipital lobe, the patient was unable to recognize familiar objects, including faces of people well-known to him (e.g., his wife), and found it difficult to discriminate among simple shapes, despite the fact that he did not exhibit any intellectual deficit. As is typical in visual agnosias, this patient showed no purely sensory deficits, showed normal eye movement patterns, and appeared to have close to normal stereoscopic depth and motion perception. Despite the severity of his visual impairment, the patient could do many other visual and object-recognition tasks. For example, even though he could not recognize an object in its entirety, he could recognize its features and could describe and even draw the object quite well – either when it was in view or from memory. Because he recognized the component features, he often could figure out what the object was by a process of deliberate problem-solving, much as the continuity theory claims occurs in normal perception, except that for this patient it was a painstakingly slow process. From the fact that he could describe and copy objects from memory, and could recognize objects quite well by touch, it appears that there was no deficit in his memory for shape. These deficits seem to point to a dissociation between the ability to recognize an object (from different sources of information) and the ability to compute an integrated pattern from visual inputs which can serve as the basis for recognition. As (Humphreys & Riddoch, 1987, p 104) put it, this patient's pattern of deficits "supports the view that 'perceptual' and 'recognition' processes are separable, because his stored knowledge required for recognition is intact" and that inasmuch as recognition involves a process of somehow matching perceptual information against stored memories, then his case also "supports the view that the perceptual representation used in this matching process can be 'driven' solely by stimulus information, so that it is unaffected by contextual knowledge."

It appears that in this patient the earliest stages in perception – those involving computing contours and simple shape features – are spared. So also is the ability to look up shape information in memory in order to recognize objects. What then is damaged? It appears that an intermediate stage of "integration" of visual features fails to function as it should. The pattern of dissociation shows the intact capacity to extract features together with the capacity to recognize objects from shape information is insufficient for visual recognition so long as the unique visual capacity for integration is absent. But "integration" according to the New Look (or Helmholtzian) view of perception, comes down to no more than making inferences from the basic shape features – a capacity that appears to be spared.

2.3.5 Evidence that cognitive penetration occurs in pre-perceptual and post-perceptual stages

Finally, there are methodological questions that can be raised in connection with the interpretation of empirical evidence favoring the continuity thesis. There are certain methodological arguments favoring the view that the observed effects of expectations, beliefs, and so on, while real enough, operate primarily on a stage of processing after what I have called early vision, some of which are summarized in the next section, but are treated at greater length in (Pylyshyn, 1999). Thus the effect of knowledge can often be traced to a locus subsequent to the operation of vision proper – a stage where decisions are made as to the category of the stimulus or its function or its relation to past perceptual experiences. There is also evidence that in other cases where beliefs and past experience appear to influence what we see, such as in perceptual learning and in the effect of "hints" on the perception of certain ambiguous stimuli, the cognitive effect may be traced to a pre-perceptual stage where the perceiver learns to allocated attention to different features or places in a stimulus. Both these cases are briefly reviewed in the next section.

2.4 Distinguishing perceptual and decision stages: Some methodological issues

Some of the arguments among researchers, concerning whether early vision is cognitively penetrable or encapsulated, rest on certain considerations of experimental methodology. The question of whether vision is encapsulated might be approached by trying to divide visual processing into stages, for example a stage that might correspond to what I have called early vision and a stage that is concerned with making decisions about what the stimulus was and what response to make to it. Such distinctions raise questions of experimental method: Given that context affects the way observers respond to a stimulus, how does one tell whether this is because the context affects how they see it, what they recognize it to be (i.e., what they see it as), how they classify it in relation to things they have seen before, or what they decide to do in a particular experimental context (i.e., what response they decide to make). The attempt to distinguish such stages has a venerable history in the study of perception, going back to the earliest days of experimental psychology. The question received a major impetus in the 1950s with the development of such theoretical instruments as Signal Detection Theory and the use of certain patterns of electrical potentials on the scalp (called Event-Related Potentials, or ERPs) and other techniques for dividing the information process into stages and for determining which stage is responsible for certain observed phenomena.

Quite early in the study of sensory processes it was known that some aspects of perceptual activity involve decisions, whereas others do not. Bruner himself even cites research using the newly developed technique of Signal Detection Theory (SDT) (Tanner & Swets, 1954) in support of the conclusion that psychophysical functions involve decisions. What Bruner glossed over, however, is that the work on signal detection analysis not only shows that decisions are involved in such psychophysical tasks as threshold measurements, it also shows that such tasks typically involve at least two stages, one of which, sometimes called “stimulus detection,” is immune from cognitive influences, while the other, sometimes called “response selection”, is not. In principle, the theory provides a way to separate these two stages and to assign independent performance measures to them: To a first approximation, detection is characterized by a sensitivity measure, usually denoted as d' , while response selection is characterized by a response bias or response criterion measure denoted as β . Only the second of these measures was thought to capture the decision aspect of certain psychophysical tasks, and therefore, according to this view, it is the only part of the process that ought to be sensitive to knowledge and utilities.

The idea of factoring visual information processing into roughly a stimulus-processing stage and a response selection stage inspired a large number of experiments directed at “stage analysis” using a variety of methodologies in addition to signal detection theory, including the “additive factors method” (Sternberg, 1969), mathematical techniques such as the use of the “attention operating characteristic” (Sperling & Melchner, 1978), the use of event-related potentials (ERPs) and other methods devised for specific situations. Numerous experiments have shown that certain kinds of cognitive malleability observed in experiments on perception is due primarily to the second of these stages—the stage at which a response decision is made (Samuel, 1981). But not all the results support this conclusion; a few studies have also shown that stages prior to response selection are also changed by changes in expectations (i.e. by the cognitive context). When I began a review of techniques for analyzing information processing into stages (which led to the analysis presented in, Pylyshyn, 1999) I had hoped that these techniques would allow us to separate those effects attributable to the perceptual stage from those attributable to subsequent decision stages. This goal was only partly achieved, however, because it turned out that the stages distinguished by these techniques are too coarse for this purpose and do not correspond exactly to the distinction that is relevant to the independence thesis. What the techniques are able to show is that certain influences, sometimes taken to demonstrate the cognitive penetration of vision, have their locus in the selection of a response and in the preparation of an actual overt response. When the effect is found to lie outside the response selection stage, however, the methods are unable to distinguish whether this occurs in what I have been calling early vision or in some other part of the information-processing stream. There is clearly much more going on when we perceive than detecting a stimulus followed by the preparation of the action of responding. For example, apart from various shape and surface computations there is the *recognition* of the

stimulus pattern as one that has been seen before. Since this sort of recognition (seeing the stimulus *as* something familiar) inherently involves accessing memory, it falls outside what I call early vision, and yet it is not a case of preparing an actual response. Thus the use of methods such as those of signal detection theory and ERP provides an asymmetrical test of the cognitive penetrability of vision. Showing that the effect of changing beliefs or expectations operates entirely at the response selection stage (i.e., it affects β but not d') shows that in this case the belief change does not influence early vision. On the other hand, showing that the effect operates at the so-called stimulus detection stage (or operates by influencing the sensitivity measure d' and not β) does *not* show that early vision is cognitively penetrable, because the detection stage includes more than just early vision.

The problem with all the techniques of stage analysis that have so far been proposed is this: Whether the technique is simple or sophisticated, it usually ends up distinguishing a stage of response preparation from everything else concerned with processing visual information. But that distinction is too coarse for our purposes if our concern is whether an intervention affects the visual process or the post-perceptual recognition-inference-decision-response process. To determine whether early vision is cognitively penetrable one needs to make further distinctions within what stage-theorists call the stimulus detection or stimulus evaluation stage. In particular one needs to factor out functions such as categorization and identification, which require accessing general memory, from functions of early vision, such as individuating objects and computing spatial relations among them, which, by hypothesis, do not. That is why we find, not surprisingly, that some apparently visual tasks are sensitive to what the observer knows, since the identification of a stimulus clearly requires both inferences and access to memory and knowledge. A more detailed technical discussion of this claim is provided in (Pylyshyn, 1999) and the reader who is interested in the underlying assumptions is invited to consult that paper.

2.5 Some examples in which knowledge is claimed to affect perception

2.5.1 “Intelligent” interpretations of inherently ambiguous information

A number of writers (Gregory, 1970; Rock, 1983) have noted that the visual system delivers unique interpretations of visual (optical) information that is inherently ambiguous, and that when it does so it invariably produces an interpretation that is “intelligent” in that it appears to take into account certain cues in a way which suggests that, to use an anthropomorphic phrase, “it knows how things in the world work”. These examples are indeed among the most interesting cases to consider from the perspective of the independence thesis, both because they constitute impressive demonstrations of smart vision and also because they provided major challenges to theories of computer vision and well as some of its most impressive successes. The successes followed the seminal work of David Marr (Marr, 1982) and are based on the discovery of certain constraints inherent in the visual system (so-called “natural constraints”). Because of the importance and far-reaching implications of this idea I will postpone this discussion until the next chapter where I consider the nature of the “architecture,” or relatively fixed structural properties of the vision system.

2.5.2 Experience and “hints” in perceiving ambiguous figures and stereograms

So far I have suggested that many cases of apparent penetration of visual perception by cognition are either cases of top-down effects occurring within the visual system (discussed in section 2.3.3), or are cases in which knowledge and utilities are brought to bear at the pre-perceptual stage (by determining where to focus attention) or at the post-perceptual stage (by determining which possible interpretation provided by early vision to favor). But there are some alleged cases of penetration that, at least on the face of it, do not seem to fall into either of these categories. One is the apparent effect of hints, instructions and other knowledge-contexts on the ability to resolve certain ambiguities or to achieve a stable percept in certain difficult-to-perceive stimuli. A number of such cases have been reported, though these have generally been based on informal observations rather than on controlled experiments. Examples include the so-called “fragmented figures” (such as illustrated in Figure 2-6 or Figure 2-7), ambiguous figures, and stereograms,

including the famous *Magic Eye*® posters that show 3D images based on what are known as autostereograms. I will now suggest that these apparent counterexamples, though they may sometimes be phenomenally persuasive (and indeed have persuaded many vision researchers), are not sustained by careful experimental scrutiny.



Figure 2-6. A famous picture of a Dalmatian dog, by R.C. James, which typically comes into view suddenly.

It is widely believed that providing “hints” can improve a person’s ability to recognize a fragmented figure such as that shown in Figure 2-6 (and other so-called “closure” figures such as those devised by Street, 1931), some of which are shown in Figure 2-7 below. Yet that claim has rarely been tested experimentally. There is some evidence that priming with completed pictures does improve recognition performance, although (Gollin, 1960) showed that training with the fragmented pictures using an ascending method of limits produced more learning than extensive training with completed pictures. In a related finding, (Snodgrass & Feenan, 1990) showed that perceptual closure can best be primed by showing fragmented figures that were partially completed. Priming by complete figures was much poorer than priming by partially completed figures. These cases, however, only show the effect of visually presented information on perceptual closure, and even then they find that partial information is better than complete information in priming identification. Since complete pictures carry full information about the identity of the objects it seems that it is not knowing the identity of the objects that is most effective, but some other perceptual factor. Perhaps the attempt to obtain closure in the partially-completed figures initiates a search for visual cues which then helps to focus attention. The partially-completed figures used by Snodgrass and Kelly allow the viewer to see both the identity of the complete figure and also the nature and location of some of the fragments that form part of the completed figure, so it provides better cues as to where to focus attention in the fragmented figure.

The effectiveness of verbal “hints” was investigated directly by (Reynolds, 1985). Reynolds used the figures taken from the Street’s Gestalt Completion Test (Street, 1931) (a few of which are shown in Figure 2-7) and found that providing instructions that a meaningful object exists in the figure greatly improved recognition time and accuracy (in fact when subjects were not told that the figure could be perceptually

integrated to reveal a meaningful object, only 9% saw such an object). On the other hand, telling subjects the class of object increased the likelihood of eventual recognition but did not decrease the time it took to do so (which in this study took around 4 sec – much longer than any picture-recognition time, but much shorter than other reported times to recognize other fragmented figures, where times in the order of minutes are typically observed).¹⁷ The importance of expecting a meaningful figure is quite general and parallels the finding that knowing that a figure is reversible or ambiguous is important for arriving at alternative percepts (perhaps even necessary, as suggested by Girgus, Rock & Egatz, 1977; Rock & Anson, 1979). But this is not an example in which knowledge acquired through hints affects the content of what is seen – which is what cognitive penetration requires. If anything, the fact that the principle effect on perception comes from knowing that a meaningful figure could be seen (in the case of fragmented figures), or the effect of knowing that a figure could be ambiguous, adds more credence to the earlier suggestion that such information initiates a search for cues as to where to focus attention, as opposed to a perceptual process. This would also explain why closure of fragmented figures takes so long to attain, compared to the very short time to perceive a picture (which appears to be on the order of a tenth of a second, see for example, Potter, 1975).

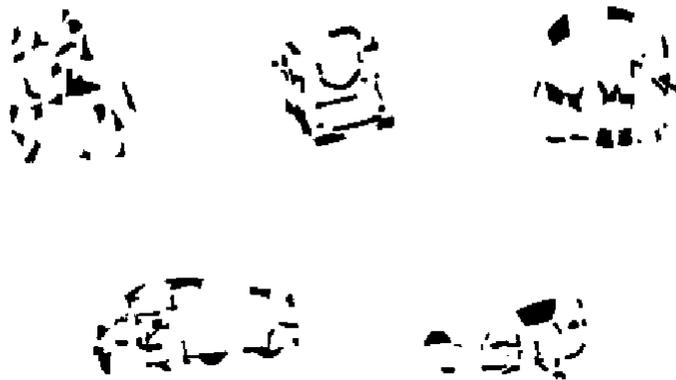


Figure 2-7 Examples of fragmented or “closure” figures used by (Reynolds, 1985) (based on Street’s “Gestalt Completion Test” Street, 1931).

Notice that the fragmented figure examples constitute a rather special case of visual perception, insofar as they present the subject with a problem-solving or search task. Subjects are asked to provide a report under conditions where they would ordinarily not see anything meaningful. Knowing that the figure contains a familiar object results in a search for cues. As fragments of familiar objects are found, the visual system can be directed to the relevant parts of the display, leading to a percept. That a search is involved is also suggested by the long response latencies (see note 17) compared with the very rapid speed of normal vision (in the order of tenths of a second, when response time is eliminated, see Potter, 1975).

What may be going on in the time it takes to reach perceptual closure in these figures may be simply the search for a locus at which to apply the independent visual process. This search, rather than the perceptual process itself, may then be the process that is sensitive to collateral information. This is an important form of intervention, from our perspective, since it represents what is really a pre-perceptual stage during which

¹⁷ Keith Humphrey, at the University of Western Ontario, frequently provides class demonstrations in which he shows fragmented figures in class to a group of students, some of whom were given written hints in advance. Judging by the latency of hand-raises, the hints have tended to speed up the recognition. Given the informal nature of this demonstration the results should be received with caution and a controlled version of the experiment seems merited. But an interesting observation that Humphrey reported is that the time taken for closure was very long – in the order of minutes, rather than the fractions of a second required for normal perception of such simple forms. Clearly something other than visual recognition is involved in such cases – most likely some sort of problem-solving based on searching for critical cues.

the visual system is indeed directed by voluntary cognitive processes – though not in terms of the content of the percept but in terms of the location at which the independent visual process is to be applied. In Chapter 4, I will argue that an important way in which cognition can affect the outcome of visual perception is by directing the independent visual system to focus attention at particular (and perhaps multiple) places in the scene.

A very similar story concerning the locus of cognitive intervention applies in the case of other ambiguous displays. When one percept is attained and observers know that there is another one, they can engage in a search for other organizations by directing their attention to other parts of the display (hence the importance of the knowledge that the figure is ambiguous). It has sometimes been claimed that we can will ourselves to see one or another of the ambiguous percepts. For example, (Churchland, 1988) claims to be able to make ambiguous figures “...flip back and forth at will between the two or more alternatives, by changing one’s assumptions about the nature of the object or about the conditions of viewing.” This is not what has been reported in experiments with naïve subjects, where the only factor that has been found to be relevant is the knowledge that the stimulus is ambiguous. Moreover, as I have already suggested, there is a simple mechanism available for some degree of control of such phenomena as figure reversal – the mechanism of spatially focused attention. It has been shown (Kawabata, 1986; Peterson & Gibson, 1991) that the locus of attention is important in determining how one perceives ambiguous or reversing figures such as the Necker cube. Some parts of a figure tend to have a bias toward one interpretation while other parts have a bias towards another interpretation; consequently changing the locus of attention may change the interpretation (e.g., there appears to be a bias toward seeing the attended parts of a figure as being closer to the viewer). If there is a bias in the interpretation of a part of the figure this will tend to influence the interpretation of the remainder of the figure. But there is no evidence that voluntarily “changing one’s assumptions about the object” has any direct effect on how one perceives the figure.

There are other cases where it has been suggested that hints and prior knowledge affect perception. For example, the fusion of stereo images, such as Figure 3-18 and even more so with stereo images made of random dots – a form of presentation invented by (Julesz, 1971) called “random dot stereograms” – is often quite difficult and was widely thought to be improved by giving people information about what they should see (the same is true of the popular autostereograms).¹⁸ There is evidence, however, that merely telling a subject what the object is or what it looks like does not make a significant difference. In fact, (Frisby & Clatworthy, 1975) found that neither telling subjects what they “ought to see” nor showing them a 3-D model of the object, provided any significant benefit in fusing random-dot stereograms. What does help, especially in the case of large-disparity stereograms, is the presence of prominent monocular contours, even when they do not themselves provide cues as to the identity of the object. (Saye & Frisby, 1975) argued that these cues help facilitate the required vergence eye movements and that in fact the difficulty in fusing random-dot stereograms in general is due to the absence of features needed for guiding the vergence movements of the eyes required in order to fuse the display. One might surmise that it may also be the case that directing focal attention to certain features (thereby making them perceptually prominent) can help facilitate eye movements in the same way. In that case learning to fuse stereograms, like learning to see different views of ambiguous figures, may be mediated by learning where to focus attention.

2.5.3 Learning to “see” differently: A case of controlling focal attention?

There is general agreement that focal attention can be directed, either extrinsically (by virtue of certain properties of the stimulus) or intrinsically (by central processes, operating voluntarily). Whichever form of attention allocation occurs, both the conditions triggering automatic allocation and the conditions that determine voluntary allocation may be modified over time. There is evidence that just as eye movements can be modulated by experience (e.g., Shapiro & Raymond, 1989), so can the allocation of attention. This

¹⁸ A commercial version of these autostereograms are the Magic Eye® 3-D posters. As of this writing, examples of these may be seen at: <http://www.magic-eye.com>. Other stereo demonstrations can be found at <http://www.vision3d.com/optical/index.shtml#stereogram>.

being the case, one might reasonably wonder whether some or all of the effects studied under the category of “perceptual learning” might not be attributable to the indirect effect of learning to allocate attention.

Clearly we can decide to focus our attention on certain parts of a scene rather than others. Earlier I claimed that this attention allocation was one of the two principle ways for cognition to intervene in influencing visual perception; the other being the post-visual determination of the identity of familiar scene contents. I suggested that such attention-allocation was responsible for the speedup in achieving perceptual closure after exposure to a previous instance of the closure figure. Similarly, the effect of certain types of experience on our ability to fuse random-dot stereograms and autostereograms was attributed to learning to focus attention on features that guide appropriate eye vergence. For example, the main thing that makes a difference in the ease of fusing a stereogram is having seen the stereogram before. (Frisby & Clatworthy, 1975) found that repeated presentation had a beneficial effect that lasted for at least 3 weeks. In fact the learning in this case, as in the case of improvements of texture segregation with practice (Karni & Sagi, 1995) is extremely sensitive to the retinal location and orientation of the visual displays – so much so that experience generalizes poorly to the same figures presented in a different retinal location (Ramachandran, 1976) or a different orientation (Ramachandran & Braddick, 1973). An important determiner of stereo fusion (and even more so in the case of the popular autostereogram posters) is attaining the proper vergence of the eyes. Such a skill depends on finding the appropriate visual features to drive the vergence mechanism. It also involves a motor skill that one can learn; indeed many vision scientists have learned to free-fuse stereo images without the benefit of stereo goggles. This suggests that the improvement with exposure to a particular stereo image may simply be learning where to focus attention and how to control eye vergence.

The improvement in a perceptual skill following learning which features are critical to the skill is a quite general phenomenon. In chapter 1 this claim was illustrated in the case of chess masters, whose memory for chess positions was found to be highly dependent on whether or not the chess positions could be interpreted in terms of a real chess match. This was taken as evidence that chess masters differ from beginners because (1) masters have a code for a large number of positions and (2) masters know where to look for significant chess-relevant patterns. It is frequently the case that expertise in a visual skill depends on finding and encoding certain special features that are diagnostic for the particular distinctions that define the expertise in question. I will present some quite general cases of this principle below.

2.5.3.1 Cultural and linguistic effects on perception

It was widely believed that how people see the world is conditioned by their culture and even by the language they speak. This thesis, called Linguistic Relativity was articulated by the anthropologist Benjamin Lee Whorf and linguist Edward Sapir and is sometimes referred to as the Sapir-Whorf hypothesis. The thesis was widely accepted during the time when the New Look in perception held sway. It was congenial to the *tabula rasa* view of human nature that pervaded both philosophical and psychological behaviorism, as well as view of the “perfectibility of human nature” that grew out of the enlightenment. It is the view that human nature is largely the product of our experiences. Although linguistic relativity in the strong Whorfian form has been discredited in the past several decades, a modified and somewhat weaker version of this hypothesis has once again seen some support (e.g., Gumperz & Levinson, 1996). Most of the recent work only supports the claim that language provides resources over and above the nonlinguistic concepts that are needed to encode the visual world (and even so, many believe that the new relativism also rests on shaky foundations, see Li & Gleitman, 2002; Pinker, 1994). Notice that the new linguistic relativism is not the same as the New Look view, which claims that what we see, and how we see, depends on our beliefs. Even if the newer evidence and arguments are sustained, the claims that they make only concern long term effects of language on visual interpretation and encoding, not the sort of effects that support the idea that vision and cognition merge continuously into one another.

2.5.3.2 The case of “expert” perceivers

Another apparent case of penetration of vision by knowledge occurs in the case of “expert” perceivers of various kinds – people who are able notice patterns that the rest of us fail to see (bird watchers, art

authenticators, radiologists, aerial-photo interpreters, sports analysis, chess masters, and so on). Not much is known about such perceptual expertise since such skills are typically highly deft, rapid, and unconscious. When asked how they do it, experts typically say that they can “see” certain properties by “just looking”. But what research is available shows that often what the expert has learned is not a “way of seeing” as such, but rather some combination of task-relevant mnemonic skills (knowing what kinds of patterns to look for) with knowledge of where to look or where to direct their attention.

The first type of skill is reminiscent of the conclusion reached by (Haber, 1966) that “preparatory set” operates primarily through mnemonic encoding strategies. It is most clearly illustrated in the work of (Chase & Simon, 1973) who showed that what appears to be chess masters’ rapid visual processing and better visual memory for chess boards, only manifests itself when the board consists of familiar chess positions and not at all when it is a random pattern of the same pieces (beginners, of course, do equally poorly on both, see Figure 1-19e). Chase & Simon interpret this as showing that rather than having learned to see the board differently, chess masters have developed a very large repertoire (they call it a vocabulary) of patterns which they can use to classify or encode genuine chess positions, though not random positions. Thus what is special about experts’ vision in this case is the system of classification that they have learned which allows them to recognize and encode a large number of relevant patterns. But, as I argued earlier, such a classification process is post-perceptual insofar as it involves decisions requiring accessing long-term memory.

The second type of skill, the skill to direct attention in a task-relevant manner, is documented in what is perhaps the largest body of research on expert perception; the study of performance in sports. It is obvious that fast perception, as well as quick reaction, is required for high levels of sports skill. Despite this truism, very little evidence of faster visual information processing capabilities has been found among athletes (e.g., Abernethy, Neil & Koning, 1994; Starkes, Allard, Lindley, & O’Reilly, 1994). In most cases the difference between novices and experts is confined to the specific domains in which the experts excel – and there it is usually attributable to the ability to anticipate relevant events. Such anticipation is based, for example, on observing initial segments of the motion of a ball or puck or the opponent’s gestures (Abernethy, 1991; Proteau, 1992). Except for a finding of generally better attention-orienting abilities (Castiello & Umiltá, 1992; Greenfield, deWinstanley, Kilpatrick, & Kaye, 1994; Nougier, Ripoll & Stein, 1989) visual expertise in sports, like the expertise found in the Chase & Simon studies of chess skill, appears to be based on non-visual abilities related to the learned skills of identifying, predicting and therefore attending to the most relevant places.

An expert’s perceptual skill frequently differs from a beginner’s in that the expert has learned where the critical distinguishing information is located within the stimulus pattern. In that case the expert can direct focal attention to the critical locations, allowing the independent visual process to do the rest. A remarkable case of such expertise was investigated by (Backus, 1978; Biederman & Shiffrar, 1987) and involves expert “chicken sexers”. Determining the sex of day-old chicks is both economically important and also apparently very difficult. In fact it is so difficult that it takes years of training (consisting of repeated trials) to become one of the rare experts. By carefully studying the experts, Beiderman and Shiffrar found that what distinguished good sexers from poor ones is, roughly, where they look and what distinctive features they look for. Although the experts were not aware of it, what they had learned was the set of contrasting features and, even more importantly, where exactly the distinguishing information was located. Beiderman and Shiffrar found that telling novices where the relevant information was located allowed them to quickly become experts themselves. What the “telling” does – and what the experts had tacitly learned – is how to bring the independent visual system to bear at the right spatial location, and what types of patterns to encode into memory, both of which are functions lying outside the visual system itself.

Note that this is exactly how I suggested that hints work in the case of the fragmented or ambiguous figures or binocular fusion cases. In all these cases the mechanism of spatially focused attention plays a central role. I believe that this role is in fact quite ubiquitous and can help us understand a large number of phenomena involving cognitive influences on visual perception (see below and section 6.5 for more on this claim).

2.5.3.3 Attention and perceptual learning

There is a large literature on what is known as “perceptual learning,” much of it associated with the work of Eleanor Gibson and her students (Gibson, 1991). The findings show that, in some general sense, the way people apprehend the visual world can be altered through experience. For example, the way people categorize objects and properties – and even the discriminability of features – can be altered through prior experience with the objects. In this same tradition, recent studies (Goldstone, 1994, 1995) showed that the discriminability of stimulus properties is altered by pre-exposure to different categorization tasks. (Schyns, Goldstone & Thibaut, 1998) have argued that categorization does not rely on a fixed vocabulary of features but that feature-like properties are “created under the influence of higher-level cognitive processes ...when new categories need to be learned ...”.

This work is interesting and relevant to the general question of how experience can influence categorization and discrimination. The claim that a fixed repertoire of features at the level of cognitive codes (though clearly not at the level of basic sensory receptors) is inadequate for categorization is undoubtedly correct (for more on this see, Fodor, 1998). However, none of these results is in conflict with the independence or impenetrability thesis as I have been developing it here for the following reasons:

- (1) Although some perceptual-learning researchers have claimed that what may be altered is the basic early-vision processes, this is far from clear from the results themselves. In all reported cases what is actually being measured is observers’ differential use of certain features compared with their use of other available features. But this could be the result of one of the two processes lying outside of early vision that were discussed earlier. These are: (a) selective attention being applied to one physically-specifiable dimension over another (e.g. one location over another, color over luminance, height over width, and so on) or (b) one perceptual feature being weighted more or less than another and/or combined in different (nonlinear) ways in the post-perceptual categorization decision-process (which could, in effect, result in the creation of different feature-clusters).
- (2) Even if the claim that there is low-level learning in early vision can be sustained (i.e., even if the effect is due to neither learning to allocate focal attention nor to post-perceptual decision processes) the claims are not directly relevant to the discontinuity thesis. The shaping of basic sensory processes by experience is not the same as cognitive penetration. The latter entails that the content of percepts (not just the discriminability of features) is rationally connected to beliefs, expectations, values, and so on—regardless of how the latter are arrived at or altered. That is the type of influence that the New Look was concerned with and that is the kind of influence that concerns us here. It is this kind of influence that is at the core of the discontinuity thesis and the whole issue of architectural constraints. The tuning of the sensitivity of sensory systems (not only organs but also cortical centers) by evolution or by prolonged experience is not the same as cognitive penetration, the determination of what we see in any particular instance by our immediate expectations, beliefs, needs, or inferences.
- (3) Finally, with regard to the genesis of visual expertise, it should be noted that there is no a priori reason why a post-perceptual decision process might not, with time and repetition, become automatized and cognitively impenetrable, and therefore indistinguishable from the encapsulated visual system. Such automatization creates what I have elsewhere (Pylyshyn, 1984a) referred to as “compiled transducers”. Compiling complex new transducers is a process by which formerly post-perceptual processing may become part of early vision by becoming automatized and encapsulated, and may even have its own local storage (see Pylyshyn, 1984a, chapter 9, for more on this point). If the resulting process is cognitively impenetrable – and therefore systematically loses the ability to access general memory, then, according to the view being advocated here, it becomes part of the visual system. Consequently, it is consistent with the present framework, that new complex processes could become part of the early vision system over time: Cognitive impenetrability and diachronic change are not incompatible. How processes can become “compiled” into the visual system remains unknown, although according to the Allan Newell’s levels-taxonomy (Newell, 1990) the process of altering the encapsulated visual system should take one or two orders of magnitude longer to accomplish than the duration of basic cognitive operations themselves (i.e. in the order of minutes

as opposed to fractions of a second) – and would very likely require repeated experience, as is the case with many of the perceptual learning phenomena.

2.5.4 Focal attention as an interface between vision and cognition

One of the features of perceptual learning already noted is that learning may lead to attention being focused on the most relevant objects, regions or properties of the visual field. Spatial, or object-based (see chapter 4) focusing of attention is perhaps the most important mechanism by which the visual system adjusts rapidly to an informationally-dense and dynamic world. It thus represents the main interface between cognition and vision – an idea that has been noted in the past (e.g., Julesz, 1990; Pylyshyn, 1989). Visual attention is a fundamental mechanism in both vision and visualization (or mental imagery) and a careful analysis of the various forms and functions of focal attention goes a long way towards explaining many phenomena of perceptual learning, perceptual organization, mental imagery and even the source of certain phenomenal experiences of the spatial extension and spatial stability of both visual percepts (discussed in chapter 1 and chapter 5) and mental images (discussed in section 6.5). Consequently chapters 4 and 5 will be devoted to a discussion of these issues. For present purposes I wish merely to note that there are logically two possible loci where a mechanism like selective attention could operate. First, it might operate on the input to the visual system, by enhancing and/or attenuating certain properties of the input. For example, it might enhance certain spatial locations or certain regions that constitute individual visual objects. Secondly, it might operate by enhancing and/or attenuating the availability of certain perceptual categories, as proposed by Bruner. This is what Bruner meant by “perceptual readiness” – it is the *ready availability* of categories of perception. From our perspective, the latter locus of attention occurs *after* the early visual process and may even include selective encoding into memory or selective retrieval from memory. If selective attention operates over the input prior to early vision, then it must operate over properties that are primitive and pre-perceptual, such as spatial location or perhaps spatial frequency, otherwise appeal to selective attention would be circular. In that case perceptual learning might consist in learning where to look or something equally basic (as suggested in section 2.5.3). On the other hand, if attention is viewed as being at least in part a post-perceptual process, ranging over the outputs of the visual system, then there is room for much more complex forms of “perceptual learning”, including learning to recognize paintings as genuine Rembrandts, learning to identify tumors in medical X-rays, and so on. But in that case the learning is not strictly within the visual system, but rather involves post-perceptual decision processes based on knowledge and experience, however tacit and unconscious these may be. In the everyday use of the term “attention” these two loci are not distinguished. Attention is viewed as any process that selects some aspect of perception from other aspects. As a consequence, the attempt to judge whether attention occurs early or late in vision has had mixed results: Evidence for both “early selection” and “late selection” theories has been found. But it remains possible, and indeed seems reasonable, that attention operates at both loci. Our position is that attention operates at both loci but *not* in between – i.e. not *within* the early vision system itself.

2.6 Conclusions: Early vision as a cognitively impenetrable system

In this chapter I have considered the question of whether early visual perception is continuous with cognition or whether it is best viewed as a separate process, with its own principles and possibly its own internal memory, isolated from the rest of the mind except for certain well-defined and highly circumscribed modes of interaction. In the course of this analysis I have touched on many reasons why it appears on the surface that vision is part of general cognition and thus thoroughly influenced by our beliefs, desires and utilities. Opposed to this interactionist view we found a great deal of psychophysical evidence attesting to the autonomy and inflexibility of visual perception and its tendency to resolve ambiguities in a manner that defies what the observer knows and what is a rational inference. As Irvin Rock, one of the champions of the view that vision is “intelligent,” has said, “Perception must rigidly adhere to the appropriate internalized rules, so that it often seems unintelligent and inflexible in its imperviousness to other kinds of knowledge.” (Rock, 1983, p 340).

Most of this chapter concentrated on showing that many apparent examples of cognitive effects in vision arise either from a post-perceptual decision process or from a pre-perceptual attention-allocation process. To this end some alleged cases of “hints” affecting perception, of perceptual learning, and of perceptual expertise were examined. I argued that in the cases that have been studied carefully, as opposed to reported informally, hints and instructions rarely have an effect, but when they do it is invariably by influencing the allocation of focal attention, by the attenuation of certain classes of physically-specifiable signals, and in certain circumstances by the development of such special skills as the control of eye movements and eye vergence. A very similar conclusion was arrived at in the case of perceptual learning and visual expertise, where the evidence pointed to the improvement being due to learning where to direct attention – in some cases aided by better domain-specific knowledge that helps anticipate where the essential information will occur (especially true in the case of dynamic visual skills, such as in sports). Another relevant aspect of the skill that is learned is contained in the inventory of pattern-types that the observer assimilates (and perhaps stores in a special intra-visual memory) and that helps in choosing the appropriate mnemonic encoding for a particular domain.

A number of clinical findings were also noted concerning the dissociation of cognition and perception which tend to substantiate the view that vision and cognition are independent systems (although some of this evidence will be presented in the next chapter). Very little has been said about the general issue of the nature of the output from the visual system. This question is taken up in the next chapter where it will be concluded that the output consists of shape representations involving at least surface layouts, occluding edges – where these are parsed into objects – and other details sufficiently rich to allow looking up parts of the stimulus in a shape-indexed memory for identification. I will also consider the possibility that more than one form of output is generated, directed at various distinct post-perceptual systems. In particular I will examine the evidence that motor control functions may be served by different visual outputs than recognition functions – and that both are cognitively impenetrable.

In examining the evidence that vision is affected by knowledge and expectations some space was also devoted to methodological issues concerned with distinguishing various stages of perception. Although the preponderance of evidence locates cognitive influences in a post-perceptual stage, we found that the sort of stage analysis methods in general use within experimental psychology, provide a decomposition that is too coarse to establish whether the locus of cognitive effects is inside or outside early vision proper. In particular, both signal detection measures and event-related potentials fail to provide a way to examine a stage that corresponds to what I have been calling early vision. So, as in so many examples in science, there is no simple and direct method – no methodological panacea – for answering the question whether a particular observed effect has its locus in vision or in pre- or post-visually processes.

The idea that early vision (which we might as well call “vision” since it is the part of the extensive overall process of acquiring knowledge through the visual modality that is *special* or proprietary to visual processing) is both complex and impervious to cognitive influences such as expectations and beliefs and desires will play an important role in our subsequent discussion about how vision interacts with the world and with what we know, with our cognitive representations. Henceforth in speaking about the connection between vision and the world or vision and visualization (mental imagery) “vision” will refer to the system that was identified in this chapter – the early vision system. The rest of what goes on when we visually perceive, being part of reasoning, recall, judgment and so on, will not be counted as part of the visual system proper. If the entire visual-cognition process were to count as “vision” then one would be forced to conclude that there is no such thing as vision proper, only cognizing. In that case there would be nothing particular to say about whether (and how) we reason using the visual system, or how what we see connects with the perceived world; at least no more to say about those connections than about the connection between how we reason about fashion and how we reason about physics, or how we reason about any pair of topics or subject matters. But as we have seen, vision is not just another subject matter to be thought about by the reasoning system. It is a system that has well-defined properties and principles of its own, so it is of considerable interest to ask how (if at all) *these* principles interact with the principle by which we reason, recall, make judgments and understand language. Such questions could not be studied with any precision if it had turned out that there was no such thing as *the visual system* as a separate and autonomous

set of processes. Luckily for us, and for a science of visual perception, this appears to be far from the case. Rather there appears to be a rich set of mechanisms and processes that we may say are *proprietary* to vision. The question of just *how* rich and complex these mechanisms and processes are is the burden of much that follows. In particular, if this technical sense of vision is to be of much interest, it must include a lot more than merely converting a retinal image into a mental image; it must include the process that allows us to see as much as we do see without benefit of what we know about the scene we are observing. We begin to explore this question in the next chapter.

3. THE ARCHITECTURE OF THE EARLY VISION SYSTEM: COMPONENTS AND FUNCTIONS

3.1 Some intrinsic architectural factors determining the visual percept

In the last chapter I suggested that many contextual and other apparently “intelligent” effects in vision come about *after* the visual system has completed its task – in other words, that they have a post-perceptual locus. But not all top-down effects in vision are cases that can be explained in terms of post-perceptual processes. Such top-down effects are extremely common in vision, and we shall consider a number of examples in this section. In particular, we will consider examples that appear on the surface to be remarkably like cases of “inference”. In these cases the visual system appears to “choose” one interpretation over other possible ones, and the choice appears to be notably “rational”. The important question for us is whether these constitute cognitive penetration. I argue that they do not, for reasons that cast light on the subtlety, efficiency and autonomy of the operation of visual processing.

In what follows I consider two related types of apparent “intelligence” on the part of the visual system. The first has seen some important recent progress, beginning with the seminal work of David Marr (Marr, 1982). It concerns the way in which the visual system recovers the 3-D structure of scenes from proximal 2D data that are logically insufficient or intrinsically ambiguous. The second type of case has a longer tradition; it consists in demonstrations of what (Rock, 1983) has called “problem-solving”, wherein vision provides what appear to be “intelligent” interpretations of certain systematically ambiguous displays (but see Kanizsa, 1985, for a different view concerning the use of what he calls a “ratiomorphic” vocabulary). I will suggest that it is likely that these two forms of apparent intelligence have a similar etiology.

3.1.1 Natural Constraints in Vision

Historically, an important class of argument for the involvement of reasoning in vision comes from the fact that the mapping from a 3 dimensional world to our 2 dimensional retinas is many-to-one and therefore non-invertible. Non-invertibility is a mathematical property commonly found in nature. For example if you know the area of a rectangle you cannot derive the lengths of the sides because there is an unlimited number of pairs of lengths that give the same product when multiplied (i.e., there are an unlimited number of different-shaped rectangles with the same area). In general there is an infinite number of 3-D stimuli corresponding to any 2-D image. Thus, for example, Figure 3-1 shows a two dimensional version of this infinite ambiguity. The line L_1 on the retina can be the projection of any (or all) of the edges E_1, E_2, E_3, \dots in the world (as long as all these lines lie on a common plane with the projected line).

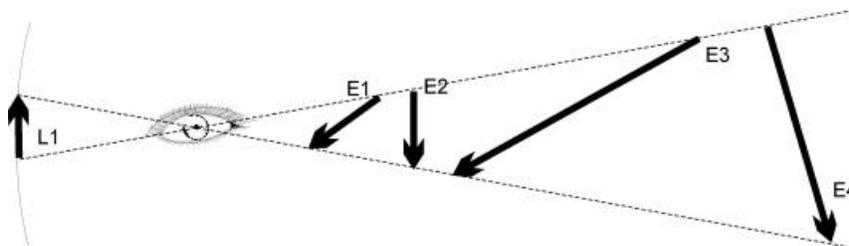


Figure 3-1. An unlimited number of oblique edges in the environment ($E_1, E_2, E_3, E_4 \dots$) project to the same 2D line (L_1) on the retina. Consequently it is a mathematical fact that if you know the exact retinal project of an edge you cannot compute the distal layout with certainty. For this reason, the 3D-to-2D projection is said to be non-invertible.

This problem is quite general and the mathematical non-invertability persists so long as no restrictions are imposed to prevent it. And yet we do not perceive a range of possible alternative worlds when we look

out at a scene. We invariably see a single unique layout. Somehow the visual system manages to select one of the myriad logical possibilities. This is not because of some magical property of our visual system: The interpretation our visual system provides really is underdetermined by the information available to our eyes. Because the information available to the visual system underdetermines the true state of affairs in the world, the unique interpretation we get always *could*, in principle, be the wrong one. When we discover a wrong interpretation we are surprised because we have learned to assume that vision is veridical. And indeed, the visual system does provide a unique interpretation that is normally consistent with the interpretation one would get from other sorts of evidence (e.g., from the evidence of touch or from walking around and observing the scene from many angles). When you do get an obviously wrong interpretation it is usually because you assimilate an unusual situation to a normal one, as in illusions such as those created by the Ames room, which is constructed to mimic an ordinary rectilinear room when viewed from a particular vantage point, but which is, in fact, highly distorted. But the converse can also occur. Richard Gregory (Gregory, 1970) constructed a real three-dimensional object which, when viewed from a particular vantage point, is perceived as an impossible one. Figure 3-2 shows the percept of an “impossible triangle” which is, of course, not impossible at all. The figure on the right shows a way to construct it, but from a specific viewpoint the viewer sees something that can’t exist!

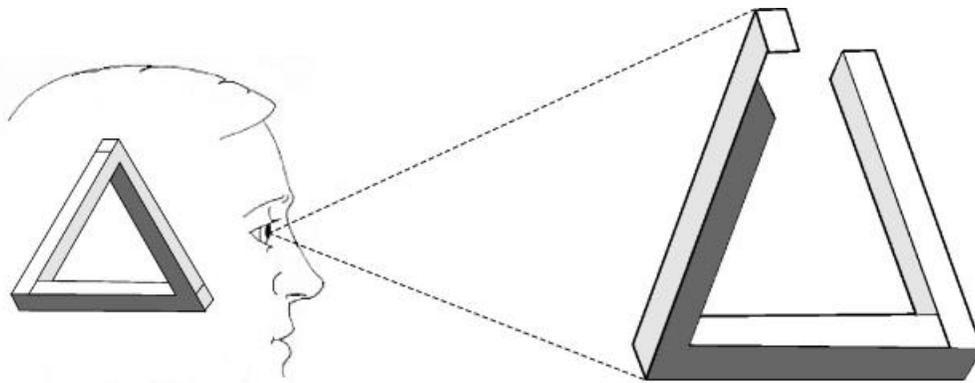


Figure 3-2. A real 3D object (on the right) which, when viewed from a particular viewpoint, is seen as an impossible object.

Yet in almost all cases our visual system provides a unique percept (usually in 3-D) for each 2-D image, even though it is possible that other options might have been computed and rejected in the process. The uniqueness of the percept (except for the case of reversing figures like the Necker cube) means that there is something else that must be entering into the process of inverting the mapping. Helmholtz, as well as most vision researchers in the 1950s through the 1970s, assumed that this was *inference from knowledge of the world* because the inversion was almost always correct (e.g., we see the veridical 3-D layout even from 2-D pictures). The one major exception to this view was that developed by J.J. Gibson, who argued that inference was not needed since vision consists in the “direct” pickup of relevant information from the optic array by a process more akin to “resonance” than to inference. Gibson’s research program (which he called “direct realism”) was an interesting and ambitious one, but failed primarily because it left no room for representations of any kind. (I will not discuss this approach here since Fodor and I devoted considerable attention to it elsewhere Fodor & Pylyshyn, 1981).

Beginning with the work of (Marr, 1982), however, a great deal of theoretical analysis has shown that there is another option for how the visual system can uniquely invert the 3D-to-2D mapping. All that is needed is that the computations carried out in early processing embody (without explicitly representing and drawing inferences from) certain very general constraints on the interpretations that it is allowed to make. These constraints do not guarantee the correct interpretation of all stimuli (the non-invertability of the mapping ensures that this is not possible in general because there *really are* other 3D configurations that could have caused the same 2D image). All that is needed is that the natural constraints lead to the correct interpretation under specified conditions which frequently obtain in our kind of physical world. If we can

find such generalized constraints, and if their deployment in visual processing is at least compatible with what is known about the nervous system, then we would be in a position to explain how the visual system solves this inversion problem without “unconscious inference”.

A substantial inventory of such constraints (which have been called “natural constraints” because they are typically stated as if they were assumptions about the natural physical world) has been proposed and studied (see, for example, Brown, 1984; Marr, 1982; Richards, 1988; Ullman & Richards, 1990). One of the earliest is the “rigidity” constraint (Ullman, 1979), which has been used to explain the kinetic depth effect. In the kinetic depth effect a set of randomly arranged moving points is perceived as lying on the surface of a rigid (though invisible) 3-D object. The requirement for this percept is primarily that the points move in a way that is compatible with this interpretation. In this case there is a natural constraint that derives from the assumption that most points in the perceived world lie on the surface of a rigid object. This assumption leads mathematically to the “structure from motion” principle which states that if a set of points moves in a way that is consistent with the interpretation that they lie on the surface of a rigid body, then they will be so perceived. The conditions under which this principle can lead to a unique percept are spelled out, in part, in a uniqueness theorem (Ullman, 1979). This theorem states that 3 or more distinct 2-D projections of 4 noncoplanar points which maintain fixed 3-D interpoint distances, uniquely determines the 3-D spatial structure of those points. Hence if the display consists of a sequence of such views, the principle ensures a unique percept which, moreover, will be veridical if the scene does indeed consist of points on a rigid object. Since in our world all but a very small proportion of feature points in a scene do lie on the surface of rigid objects, this principle ensures that the perception of moving sets of feature points is more often veridical than not.¹⁹ It also explains why we see structure from certain kinds of moving dot displays, as in the “kinetic depth effect” (Wallach & O’Connell, 1953).

Another set of constraints that apply in the case of a world consisting only of blocks entirely of polyhedral objects (the so-called “blocks world” that was often used as a test-bed for investigating ideas in computer vision) concerns the requirement of consistency on labels of edges. If an edge is assumed to be concave at one end, where it forms part of a vertex, then it must also be concave at its other end where it forms part of another vertex. But if such a labeling of the second vertex is physically impossible in the blocks world, then that label must be discarded as inconsistent. Such a simple label-consistency constraint arises in part from the physical nature of edges and vertices and turns out to be a strong constraint that makes it possible to give a unique labeling to most images of scenes containing blocks. The way this sort of constraint gets propagated until it uniquely determines the 3D labeling of a scene is typical of how natural constraints operate in vision. In this way a constraint that arises from physical properties of (our sort of) world, together with certain assumptions (e.g. that the scene consists entirely of rigid blocks) makes it possible to recover the 3D structure of a blocks world despite the fact that such a recovery is logically not unique (i.e., there is an unbounded number of real world 3D edges that could lead to any of the 2D images that are projected onto our retinas).

But the nature of the physical world is only part of the reason that the vertex labeling system works. The other part is that we may be justified in making a certain assumption about the non-accidental nature of the image projected on our retinas. In a world like ours certain things are overwhelmingly more likely to occur than others. A good example is the assumption that three co-terminal lines in an image arise from three edges of objects that come together at one point in 3D space. Not only does such an assumption not follow from the laws of physics or geometry, it is easily thwarted by simply constructing a collection of wire segments, or even edges of different blocks, as shown in Figure 3-3. But such a coincidence of edges in 3D would be *accidental* in a special technical sense, namely, if you changed your point of view even slightly the edges would no longer project as lines that come together at a common point.

¹⁹ The “rigidity” constraint is not the only constraint operative in motion perception, however. In order to explain the correct perception of “biological motion” (Johansson, 1950) or the simultaneous motion and deformation of several objects, additional constraints must be brought to bear.

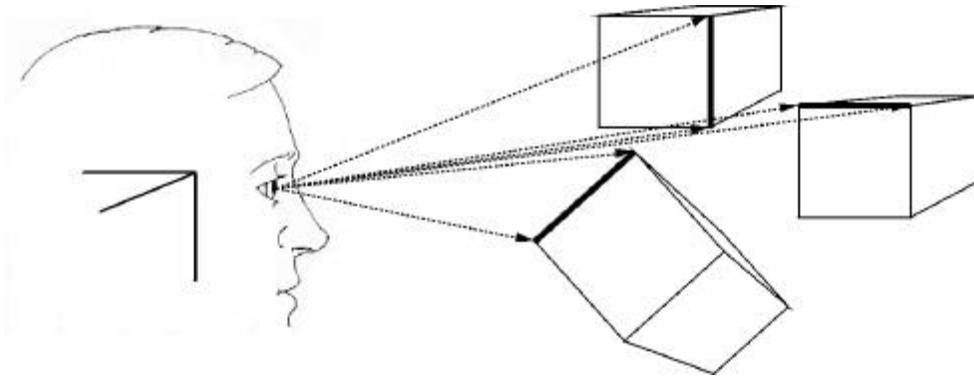


Figure 3-3. It is easy to set up a situation in which certain retinal patterns occur “accidentally” in that even the slightest change in the viewpoint will alter the coincidences on the retinal pattern.

The rarity and vulnerability of such special alignments to even small movements warrants the assumption that if a pattern such as a Y, involving the coincidence of three lines, does occur in an image it is most likely due to the fact that three edges did actually meet at a common point in the 3D scene. Such properties are called “non-accidental” and form the basis for a number of principles, which, while not inevitably true, are ones that it would be reasonable to build into a visual system. Non-accidental properties are particularly important in human and animal vision because we generally move about and can easily discover whether or not such image properties as coincidence are maintained with small changes in viewpoint. These image properties allow one to interpret a 3D scene by following certain simple principles of “natural constraints.”

3.1.1.1 An example of the use of natural constraints in feature labeling

To illustrate the way in which such natural constraints can be used to restrict the permissible 2D-to-3D mapping, consider the simplified world of blocks. Perception of such a “micro-world” was one of the first applications where natural constraints were used in computer vision (see Mackworth, 1973, for a clear description of the historical development of techniques in this area). In this approach, the problem of parsing a scene consisting of blocks, proceeds by the assignment of “labels” to individual edges in the 2D image. These labels allow us to group the parts (or features) into ones that belong to the same object and to specify which object is in front and which behind, and so on. The goal is to be able to provide a qualitative description of a scene that is rich enough to make it possible to recognize the objects in the scene, and to characterize their shapes and their relative locations.

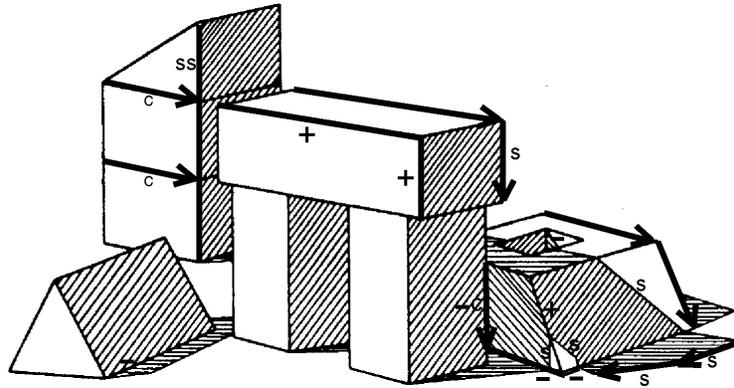


Figure 3-4. A typical blocks scene that can be analyzed using the Waltz labeling system. The analysis would reveal which lines go together to form faces and blocks, which lines separate shadow from light, which faces are in front of (and occlude) other faces, which are the outside (bottom or back) faces, thus providing a qualitative description of the scene. The labels on some of the edges are discussed in the text. (From Waltz, 1975)

Consider a scene such as the one in Figure 3-4 above, consisting of rectilinear blocks of various sizes arranged in a haphazard manner. Let us assume that the lines in the image corresponding to the edges of blocks are clearly identified. What is the minimum that we need in order to have a useful analysis of the scene? Clearly we need to segregate (or “individuate”) each of the blocks and specify which edges, vertices, and surfaces belong with which block. We also need to characterize the spatial layout of the blocks: which blocks are in front of which, which are on top of which, and so on. A qualitative solution to part of this problem would be achieved if we could label each line in the 2-D scene in some coherent and meaningful way. For example, we should be able to say that a certain line in the 2-D scene corresponds to the top edge of a particular block, another line corresponds to the edge of a certain block that occludes another block, and so on. In building a system that generates such a description, much thought and experimenting must go into the selection of an appropriate set of labels so that in the end two conditions are met: (1) it is possible to assign a unique set of labels to a scene that is perceptually unique (at least to human observers), and (2) the labeling so assigned provides a meaningful analysis of the scene that can be used for such subsequent purposes as scene recognition. A set of labels meeting these conditions was developed by David Waltz in his Ph.D. dissertation (see an abridged version in Waltz, 1975). He found a basic set of 11 line labels that met these two conditions for a world that consists of blocks. We consider a subset of 4 of his labels, illustrated in Figure 3-5. The labels tell us whether a line segment is concave (such as the inside step edge in Figure 3-5) or convex, and whether it is an outside edge of a block with the block on its left or an outside edge with the body of the block on its right. Following Waltz’s notation we label these four types of edges using the symbols + and – for the inside edges, and use arrows to indicate outside occluding edges.

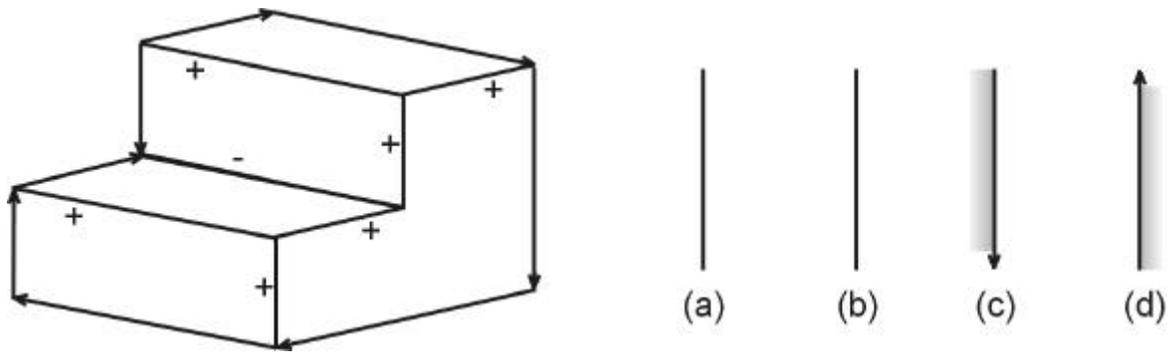


Figure 3-5: Illustration of a simplified line-labeling scheme. Labels specify the type of 3D edge that corresponds to each line in the 2D image. Labels (c) and (d) refer to outside occluding edges with the block being on the left or on the right, respectively (using a “left hand rule” – if you place your thumb in the direction of the arrow your left hand will wrap around the edge of the block).

The labels are interpreted as follows: a “+” indicates that the edge in the scene is convex, a “-” indicates that it is concave and arrows on the line indicate that it is an outside edge (using the left hand rule so that placing your hand around the line with your thumb in the direction of the arrow results in your fingers wrapping around the outside edge of the block). In the original Waltz labeling scheme there were 11 different labels (Figure 3-4 also shows an S label for “shadow”, an SS label for “self-shadow” where the shadow is cast by the same block as the one on which it falls, and a C label for a “crack” or edge where two objects would separate if moved apart). Notice that the lines we are labeling are *image* lines, so that at the beginning of this analysis we don’t know what their 3D interpretation will be. What we must do is label them with all possible labels and hope that as the analysis proceeds we will be able to eliminate some of the labels (this is the same general process used in grammatical analysis of sentences: We begin by assigning all possible parts of speech to words and then as the analysis proceeds we use grammatical rules to pare them down to the permissible ones).

The parsing system begins by assigning labels to lines that form a vertex (i.e., it labels the edges that terminate at a junction). Each type of 2-line image vertex can mathematically have 4 x 4 or 16 combinations and each type of 3-line image vertex could logically have 64 possible combinations of labels in our simplified 4 label system. Three distinct types of trihedral junctions are recognized as part of the labeling scheme (referred to as Y, T and Arrow junction), making a total of 192 trihedral junction labels and 16 dihedral junction labels. What makes the analysis possible is that *most of these label combinations cannot occur in the physical world*. The possible combinations that are physically possible (assuming we are only dealing with a world of blocks) are shown in Figure 3-6 for the four types of vertices we have considered. Waltz’s contribution was to identify 11 different edge labels and then by a tour-de-force to enumerate all the physically possible vertex types. He did this for dihedral and trihedral vertices by imagining a cube cut into 8 cubic regions (octants) and then considered what each of the corners would look like from every distinct perspective when one of the octants was filled with a solid square, then when two octants were filled, and so on up to seven octants being filled. The octant process allowed Waltz to enumerate all possible junctions for every possible configuration that creates dihedral or trihedral junctions in a world of rectilinear blocks. The result of this inventory actually turned out to be a relatively small list that includes the 18 junction labels shown in Figure 3-6, out of a logically possible 208 junctions based on this set of labels. Notice that a very large number of junction labels simply cannot occur in a real world of blocks (of course they can occur if we expand the world to include other kinds of shapes, which is why the Waltz technique is of limited value in real vision, except to illustrate the principle of natural constraints and label propagation). Notice that an “L” junction between two lines cannot be due to a part of a scene in which the two edges are of the type labeled “-”. That would require a situation with no vertical edge

in view at the junction – a situation that is physically impossible in a blocks world. When the inventory of possible vertices is complete, we end up with the L, Y, T and Arrow vertices shown in Figure 3-6.²⁰

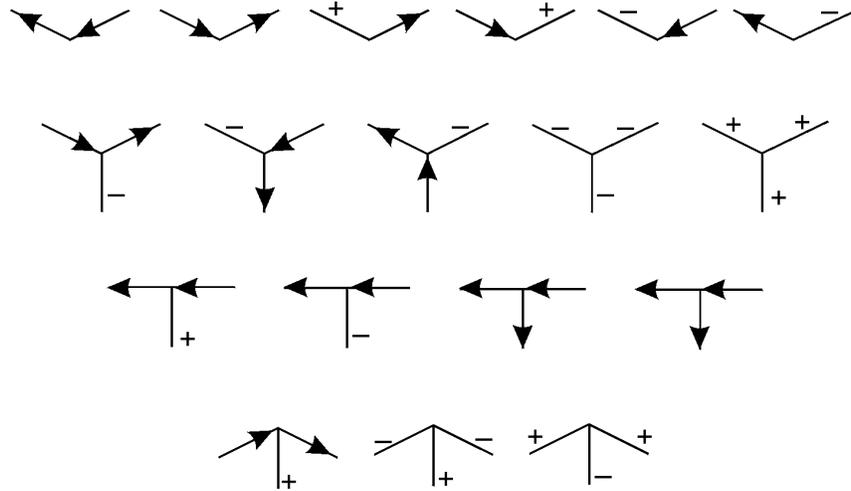


Figure 3-6. This figure shows all the physically possible vertex types that can occur in a blocks world. Only 18 of the total of 208 logically possible ones are physically permissible in this world.

The way these line and vertex labels are used in assigning a labeling to the figure is by considering all possible labels at a vertex and then tracing each line to a second connected vertex. Notice the central role that tracing plays here, and has played in our appeal to label propagation to explain some of the human vision phenomena that we saw in Chapter 1. We assume that a line must have the same label at each end – i.e. since a line corresponds to a particular real physical edge it cannot change from, say, being concave to being convex with no intervening junction. Such an assumption is a typical “natural constraint,” and constraints such as these play an important role explaining the apparently “intelligent” nature of vision. To apply the technique known as “label propagation” (or sometimes “constraint propagation”) we need to consider each pair of connected junctions and ask whether the line label that one of them allows for a particular line is a label allowed at the other junction. In other words, we trace a line from one junction to another and check whether the junction at either end prohibits that label (i.e. whether the line label in question occurs in any of the vertices listed in Figure 3-6). If it is not, then that particular label is eliminated from the candidate labels for that particular edge. Thus the pair of vertices show in Figure 3-7 below cannot occur if they are to share a common edge, since that line would have to be labeled “+” according to the top vertex whereas the label “+” is prohibited on the corresponding edge of the bottom vertex. Hence the putative labels assigned to the connecting line by one or the other vertex must be eliminated by going back to the list of vertex types (type Y or Arrow vertex in Figure 3-6) and choosing another possible label for that vertex type from the permissible list. This elimination can then be iterated and will result in the elimination of other line and vertex labels and so on. If we are lucky, the effect propagates through the network of vertex and line labels in a domino effect until all and only a consistent set of labels remains. At that point the diagram has been successfully analyzed within the limits of the set of labels provided by the technique.

²⁰ This is a highly simplified version of Waltz’ labeling scheme, as developed for pedagogical purposes by (Winston, 1984). In this version, only 4 types of line labels (illustrated in Figure 3-5) are used and some vertex types (e.g., those that include 4 edges, such as the K vertex) are omitted. The complete Waltz set includes over 50 line labels. These can generate over 300 million logically possible junctions of which only 1790 are physically possible (see Waltz, 1975).

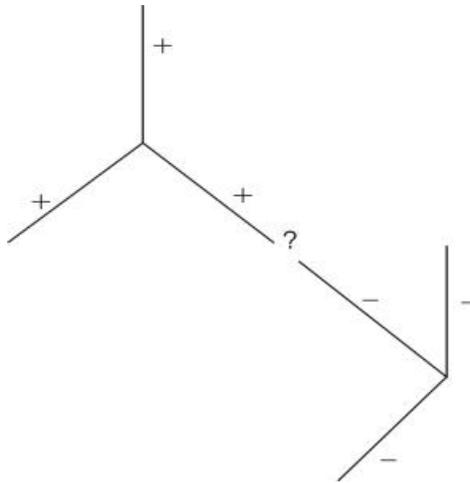


Figure 3-7: The top vertex shares a line with the bottom vertex, but the labels given to the connecting line are incompatible – it is not physically possible to have an single edge with two different labels. The pattern is then ruled out by the consistency constraint so one or the other vertex has to be relabeled using some other Y or Arrow label from Figure 3-6.

Such a constraint-propagation technique, when used in conjunction with a richer set of line labels (Waltz, 1975), generally results in the elimination of all but the perceptually-admissible labels for the figure. Ambiguous figures such as the Necker cube end up with two permissible *consistent* labelings and certain impossible figures (such as the “devil’s pitchfork in Chapter 1 and the impossible triangle illustrated in Figure 3-2) end up with no consistent set of labels. A similar story could in principle be told for a world other than the blocks world: perceptually ambiguous stimuli (such as the Necker cube shown in Figure 3-8) have at least two labelings not prohibited by some “natural constraint”. The consistent labeling that remain after this constraint propagation allow one (in some cases with the addition of other grouping principles) to figure out which lines go together to form faces and which faces occlude other faces, and so on.

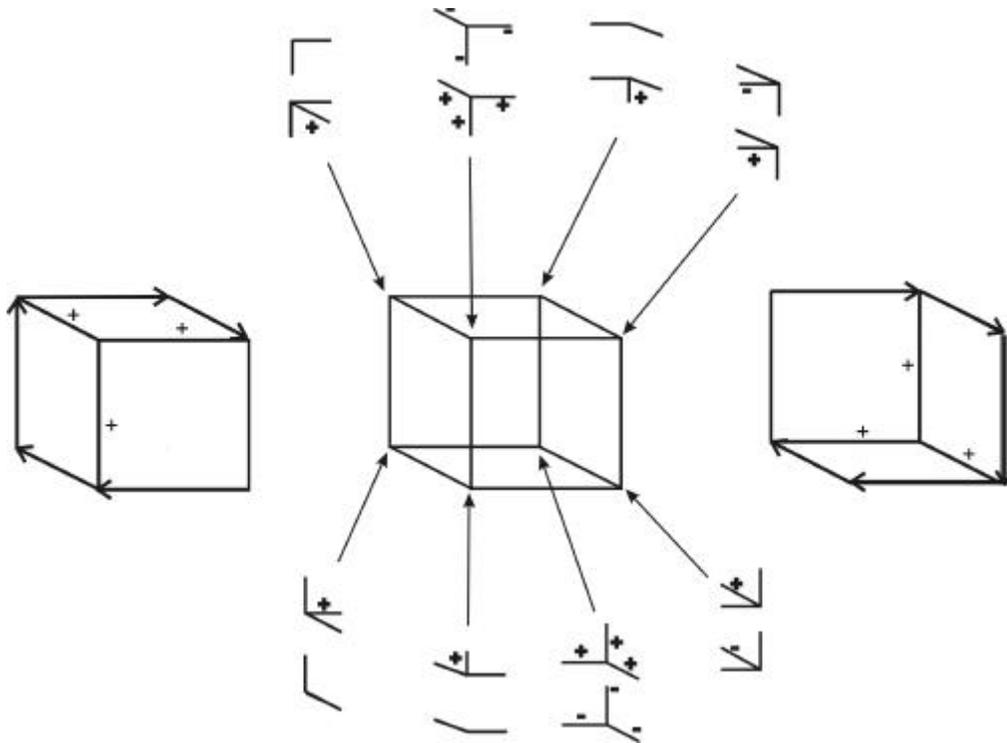


Figure 3-8. Labels of possible vertices for a Necker cube lead to two distinct sets of consistent labels, corresponding to the two interpretations shown here.

The set of labels described above, invariably allows for multiple interpretations not only of figures such as the Necker cube, but also of figures which our visual system interprets as univocal and free of ambiguities. One of Waltz's discoveries is that if the set of line labels is judiciously expanded, to include shadow edges, as well as "cracks" which are edges that would become outside edges if the abutting blocks were moved apart, then the range of interpretations is decreased, even though the number of possible vertex labels is greatly increased. By combining these various types of edges one gets about 50 different kinds of edge labels (instead of the 4 we have used in the above illustration) and also increases the number of vertex shapes from 4 to about 10, thereby increasing the combinatorially possible vertex labelings from the 208 we had to over 3 billion! Yet despite the large number of possible alternative labels for each vertex, the number of physically possible labelings only increases from 18 to around 1790. An enormous increase in the fineness of distinctions leads to an increase in number of labeling, as expected, but provides more opportunity for natural constraints to be felt. Indeed, Waltz discovered that the stronger constraints allow almost any blocks world scene to be given a unique parsing (except for those cases where we would see the scene as ambiguous, as well as a few other cases where the constraints fail to provide a unique analysis).

The application of constraints in this example works very much like the way that a computer spreadsheet (such as Excel) works. A set of requirements that must be met among rows and columns is provided (often in the form of equations) and each time one of the entries changes, the spreadsheet attempts to alter the contents of unfilled cells so that the constraints hold. In the case of vision, however, the constraints have to be discovered in nature and tested against the visual system to determine whether the candidates are indeed ones that the visual system respects. We will see later that not every constraint in the world is embedded in the visual system and in fact many extremely strong (and common) real-world constraints are not mirrored by visual system constraints, so that we can end up seeing things we know are impossible (several examples of physically impossible situations that we readily perceived are sketched in section 3.1.3).

3.1.1.2 Other constraints: The "rules" of visual analysis

In a delightful book, Donald Hoffman lists 35 of these constraints, which he calls “rules” (Hoffman, 1998). Here are a few of them (notice that they rely on the assumption that the image property in question is “non-accidental,” which means that it will continue to hold despite small changes in viewpoint):

1. Interpret a straight line in an image as a straight line in 3D.
2. If the tips of two lines coincide in an image, then interpret them as coinciding in 3D.
3. Interpret lines collinear in an image as collinear in 3D.
4. Interpret elements nearby in an image as nearby in 3D
5. Interpret a curve that is smooth in an image as smooth in 3D
6. Interpret a curve in an image as the rim of a surface in 3D.

What is perhaps most surprising is how powerful these simple principles are – they can result in the 2D-to-3D inverse mapping becoming univocal in very many naturally-occurring circumstances, resulting in the 3D interpretation of an image being unambiguous. What is also important is that the principles are not determined by either geometry or by physical law – they can be easily violated, as Figure 3-3 shows. Rather, they are principles that frequently apply in a world populated by solid coherent objects – a world in which most visual elements (say bits of texture) are on surfaces and therefore when they are close together they remain close together when one changes one’s viewpoint slightly or when the object moves. Similarly because most of what we see in the world (unlike what fish see) consists of the surface of objects, only a very small percent of each image consists of outer edges, and when they do, they appear as contours at just the point where the surface “turns the corner” or presents a rim. This is why we can usually get a great deal of information about an object’s shape from its profile (as specified by Rule 6). The latter rule, by the way, is one of a series of remarkable closely-related principles, discovered by Jan Koenderink (Koenderink, 1990) and others, that can be shown mathematically to hold, given certain assumptions about the nature of objects that are common in our particular kind of world, and in particular given the assumption that the image property is non-accidental. These principles allow one to reconstruct 3D shapes given both outside contours (profiles) and inside contours (concave and convex dimples and mounds).

The principles are not only concerned with properties of projective geometry. Some principles depend on facts that are true of our world, and might not hold of other physically possible worlds. One such principle concerns the direction of light. Since we travel primarily on the surface of the earth with the sun overhead, the direction of light is invariably from the top. This simple fact allows certain kinds of ambiguities to be resolved. This can be seen from Figure 3-9, where both mounds and craters (depressions) can be seen. The way we tend to see this picture depends on the fact that the visual system acts as though it tacitly assumes that the light comes from above. This can be seen by turning the figure upside-down: doing so inverts the mound and crater percepts!

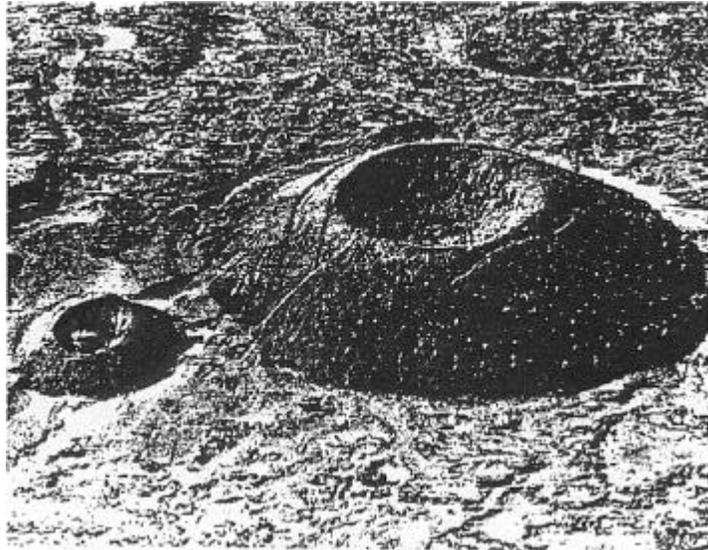


Figure 3-9. This figure shows both craters and mounds. The selection of which is seen is sensitive to the direction of light and shadows, as can be seen by turning the page upside-down, which generally reverses the craters and mounds.<ref?>

Examples of natural constraints that apply to more general situations are ones based on the fact that matter is predominantly coherent and that most substances tend to be opaque. Together these lead to the principle that neighboring elements on an image, as well as elements that move with a similar velocity, tend to arise from points on the surface of the same object. Another closely related constraint that has been used in computing depth from pairs of stereo images includes the (frequently, but not universally valid) principle that for each point on one retina there is exactly one point on the other retina that arises from the same distal feature, and the principle that neighboring points will tend to have similar disparity values. These principles allow a unique interpretation of a pair of stereo images (see Marr, 1982, pp. 111-159) because they provide guidance in solving a central problem in stereo image analysis, known as the correspondence problem: Which element in the left image should be paired with which element in the right image? Clearly we should pair those elements that arise from the same element in the 3D scene – but how do we know which pairs have that property? Principles such as those sketched above provide a basis for solving this problem in a way that is *usually* correct (in our kind of world).

Another example of the use of a constraint such as rigidity, is the model that Michael Dawson and I developed to explain why successive presentation of visual elements are seen as one pattern of apparent motion rather than another. Although one can implement many different ways of pairing an element in the first display with some particular element in the second display, it is important that this be done in a principled way and also that it be done in a way that respects any known neurophysiological constraints. This means appealing to a general constraint that holds in the world (a natural constraint) and it also suggests that the implementation should use only local information and compute correspondences based on local interactions. Since the computations in early vision tend to be done in parallel, they tend to be based on retinally-local information and connections. In our model, each pair of logically possible correspondences between one of the 4 elements in image 1 and one of the 4 elements in image 2 is considered (there are 4! or 24 of these). The relative (vector) motion of each candidate pair is compared with the relative motion of its neighbors. These potential pairings are each given weights by an iterative process. The more similar the relative motion of a particular pair is to that of its neighbors, the greater the weight given to it. In the end, the correspondence pairs left with the greatest weight represents the winning correspondence. This scheme is a direct reflection of the rigidity constraint, since it favors correspondences that constitute motions most like that of its neighbors, which is what one would expect if the elements were on the surface of a rigid object. Moreover this scheme relies on only local comparisons. The correspondences computed by this relaxation scheme bear a close relation to those actually observed with human subjects. For example, Figure

3-10 shows two different correspondences, out of a possible 24, each of which corresponds to a different apparent motion. The two curves show apparent motions that correspond to a rigid movement of the group of 4 objects, but only one of these, the one shown as a solid line, is computed based on local interactions. This solid line also corresponds to the way that observers tend to perceive this motion. In these cases, as well as a variety of others, the motion prediction that is based on a local implementation of a rigidity constraint is the one actually observed.

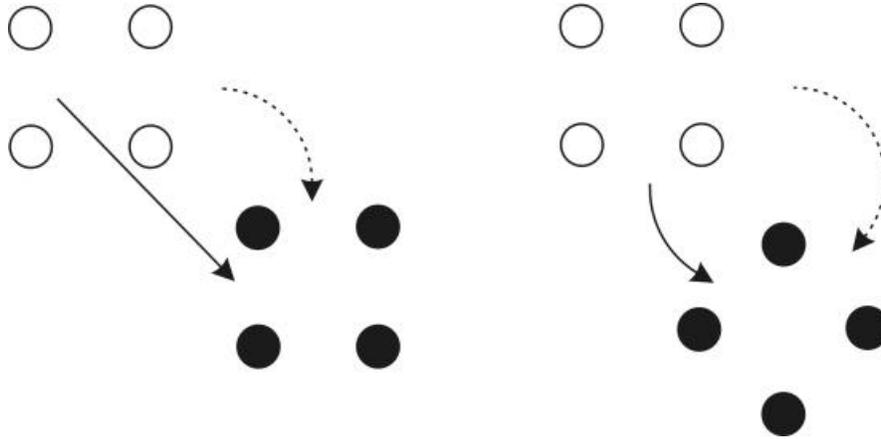


Figure 3-10. Illustration of the apparent motion predicted by a model that favors the interpretation corresponding to the elements being on the surface of a rigid object. Open circles are the configuration at time 1 and filled circles are the configuration at time 2. The solid and dotted curves are two possible correspondences between elements in the two frames that maintain the rigid configuration of 4 elements. The solid ones are the paths actually seen by observers. In each case they are the ones that favor correspondences in which the vector displacements of pairs of elements are most similar to that of its neighbors. (Based on Dawson & Pylyshyn, 1988).

This way of solving the correspondence problem is closely related to the way I suggested that the visual system solves the problem of providing a 3D interpretation of a 2D pattern, despite the fact that the 3D-to-2D mapping is logically indeterminate. The solution to both these problems involves assigning an interpretation that favors some general property that holds in our world. This process involves quite different principles than those assumed in a Bruner's or in Helmholtz' analysis. The latter would say that the visual system infers the perceived shape (or motion) by hypothesizing, say, that the elements lie in a certain particular 3-D configuration, and then would attempt to verify this hypothesis. This way of dealing with the indeterminacy problem relies on expectations of what is likely to be in the particular scene being viewed. Consequently, if the observer had reason to believe that the points did not lie on the surface of a moving rigid object, that hypothesis would not be entertained, or at least would be given low credence. But this is patently false of our visual system. For example, experiments on the kinetic depth effect are generally carried out on a flat surface, such as a computer monitor or projection screen, which subjects know is flat; yet they continue to see the patterns moving in depth. By contrast, the natural constraint view says that the visual system is so constructed (through evolution) that a certain sort of rigid interpretation will be the one automatically given (independent of knowledge of the particular scene – indeed, despite knowledge to the contrary) whenever it is possible – i.e., whenever such a representation of the distal environment is consistent with properties of the proximal stimulus. Since in our world (as opposed to, perhaps, the world of a jellyfish) most moving features of interest do lie on the surface of rigid objects, this constraint will generally lead to veridical perception.

The idea that early vision embodies, but does not explicitly represent, certain very general constraints that require vision to derive representations that are often veridical in our kind of physical world, has become an important principle in computer vision. The notion of “our kind of world” includes properties of geometry and optics and includes the fact that in visual perception the world presents itself to an observer in

certain ways (e.g., projected approximately at a single viewpoint). This basic insight has led to the development of further mathematical analyses and to a field of study known as “observer mechanics” (Bennett, Hoffman & Prakash, 1989). Although there are different ways to state the constraints – e.g., in terms of properties of the world or in terms of the use of “general purpose models” of objects (Lowe, 1987; Zucker et al., 1975), or even in terms of some world-independent mathematical principle, such as “regularization” (Poggio, Torre & Koch, 1990) – the basic assumption remains that the visual system follows a set of intrinsic principles independent of general knowledge, expectations or needs. The principles express the built-in constraints on how proximal information may be used in recovering a representation of the distal scene. Such constraints are quite different from the Gestalt laws (such as proximity and common fate) because they do not apply to properties of the proximal stimulus, but to the way that such a stimulus is interpreted or used to construct a representation of the distal perceptual world. In addition, people (like David Marr) who work in the natural constraint tradition often develop computational models that are sensitive to certain general neurophysiological constraints. For example, the processes tend to be based on “local support” – or data that come from spatially local regions of the image – and tend to use parallel computations, such as relaxation or label-propagation methods, rather than global or serial methods (Dawson & Pylyshyn, 1988; Marr & Poggio, 1979; Rosenfeld et al., 1976).

3.1.2 On “Intelligence” and “Problem-solving” in vision

In addition to the examples discussed above, there are other cases of apparently “intelligent perception” that differ from the cases discussed above because they seem to involve more than just the 2-D to 3-D mapping. These include many examples that are reviewed in the important book by Irvin Rock (Rock, 1983) where a strong case is made that vision involves “intelligent perception” or even “problem solving”. In what follows I argue that these cases represent the embodiment of the same general kind of implicit constraints as those studied under the category of natural constraints, rather than the operation of reasoning and problem-solving. Like the natural constraints discussed earlier, these constraints frequently lead to veridical percepts, yet, as in the amodal completion examples discussed earlier (e.g., section 2.3.2) they often also appear to be quixotic and generate percepts that do not bear any rational connection to the rest of the scene nor to what might rationally be expected in the scene. As with other natural constraints, the principles are internal to the visual system and are not sensitive to beliefs and knowledge about the particulars of a scene, nor are they themselves available to cognition.

Paradigm examples of “intelligent perception,” cited by (Rock, 1983), are the perceptual constancies. We are all familiar with the fact that we tend to perceive the size, brightness, color, and so on, of objects in a way that appears to take into account the distance of the objects from us, the lighting conditions, and other such factors extrinsic to the retinal image of the object in question. This leads to such surprising phenomena as different perceived sizes of afterimages when viewed against backgrounds at different distances (retinal images, such as produced by an afterimage, appear larger when viewed against a more distant background – following a principle known as Emmert’s Law). In each case it is as if the visual system knew the laws of optics and of projective geometry and took these into account, along with retinal information from the object and from other visual cues as to distance, orientation, as well as the direction and type of lighting and so on. The intelligent way that the visual system takes these factors into account is striking. Consider the example of the perceived lightness (or whiteness) of a surface, as distinct from the perception of how brightly illuminated it is. Observers distinguish these two contributors of objective brightness of surfaces in various subtle ways. For example if one views a sheet of cardboard half of which is colored a darker shade of gray than the other, the difference in their whiteness is quite apparent. But if the sheet is folded so that the two portions are at appropriate angles to each other, the difference in whiteness can appear as a difference in the illumination caused by their different orientations relative to a light common source. In a series of ingenious experiments, (Gilchrist, 1977) showed that the perception of the degree of “lightness” of a surface patch (i.e., whether it is white, gray or black) is greatly affected by the perceived distance and orientation of the surface in question, as well as the perceived illumination falling on the surface – where the latter were experimentally manipulated through a variety of cues such as occlusion, or perspective.

(Rock, 1983) cites examples such as the above to argue that in computing constancies, vision “takes account of” a variety of factors in an “intelligent” way, following certain kinds of “rules”. In the case of lightness perception, the rules he suggests embody principles that include: “...(1) that luminance differences are caused by reflectance-property differences or by illumination differences, (2) that illumination tends to be equal for nearby regions in a plane ...and (3) that illumination is unequal for adjacent planes that are not parallel” (Rock, 1983, p 279). These are exactly the kinds of principles that appear in computational theories based on natural constraints. They embody general geometrical and optical constraints, they are specific to vision, and they are fixed and independent of the particulars of a particular scene. Lightness constancy is a particularly good example to illustrate the similarities between cases that Rock calls “intelligent perception” and the kind of natural constraint cases we have been discussing, because there are at least fragments of a computational theory of lightness constancy (more recently these have been embedded within a theory of color constancy) based on natural constraints that are very similar to the principles discussed above (see, for example, Maloney & Wandell, 1990; Ullman, 1976).

Other examples are cited by Rock as showing that perception is not only “intelligent” but involves a type of “problem solving.” I will examine a few of these examples in order to suggest that they bear a striking resemblance to the natural constraints examples already discussed. The examples below are also drawn from the ingenious work of Irvin Rock and his collaborators, as described in (Rock, 1983).

Chapter 1 (Figure 1-15 and Figure 1-16) described perception through an anorthoscope, or what some people call the Zollner-Parks phenomenon (sometimes also called the eye-of-the-needle phenomenon). In these studies, a form is shown through a narrow slit as the slit moves back and forth across the form, producing a (somewhat impoverished) percept of the entire figure. But when the line segments that are visible through the slit stop short of the edge of the slit (so it no longer looks like the form is seen *through* the slit), a percept of the form does not occur. (Rock, 1981) constructed an apparatus (shown in Figure 3-11) that presents the same view to an observer that would have occurred in a genuine anorthoscopic presentation (shown on the left), but also allows the slit to be widened so that the line segment seen through the slit stops short of the edges of the slit (shown on the right). In this case the perception of a shape behind the contour does not occur, suggesting that the visual system takes into account the evidence that the moving slit does not in fact present a view of a stationary form behind it.

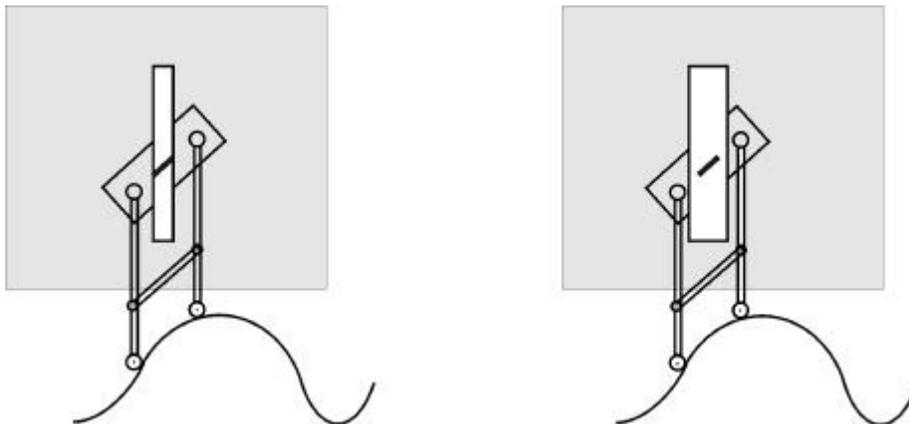


Figure 3-11. A trick version of the anorthoscope presentation. The contour segment seen through the moving slit does not reach the edge of the slit. In this case no percept of the entire form occurs. (Based on Rock, 1981)

Another example uses a familiar phenomenon of early vision in which the perception of motion is created in certain flicker displays – so-called apparent or phi motion. In these displays, when pairs of appropriately separated dots (or lights) are displayed in alternation, subjects see a single dot moving back and forth. The conditions under which apparent motion is perceived have been investigated thoroughly. From the perspective of the present concern, one finding stands out as being particularly interesting. One

way of describing this finding is to say that if the visual system is provided visually with an alternative “reason” why the dots are alternatively appearing and disappearing, then apparent motion is not seen. One such “reason” could be that an opaque object (such as a pendulum swinging in the dark) is moving in front of a pair of dots and is alternately occluding one and then the other. Experiments by (Sigman & Rock, 1974) show, for example, that if the alternation of dots is accompanied by the appearance of what is perceived to be an opaque surface in front of the dot that has disappeared, apparent motion is not seen (Figure 3-12B). Interestingly, if the “covering” surface presented over the dots is perceived as a transparent surface, then the apparent motion persists (Figure 3-12A). Moreover, whether or not a surface is perceived as opaque can be a subtle perceptual phenomenon since the apparent motion can be blocked by a “virtual” or “illusory” surface as in Figure 3-13A (since the opaque surface moving back and forth “explains” why the dots are not seen at that location), though not in the control Figure 3-13B.

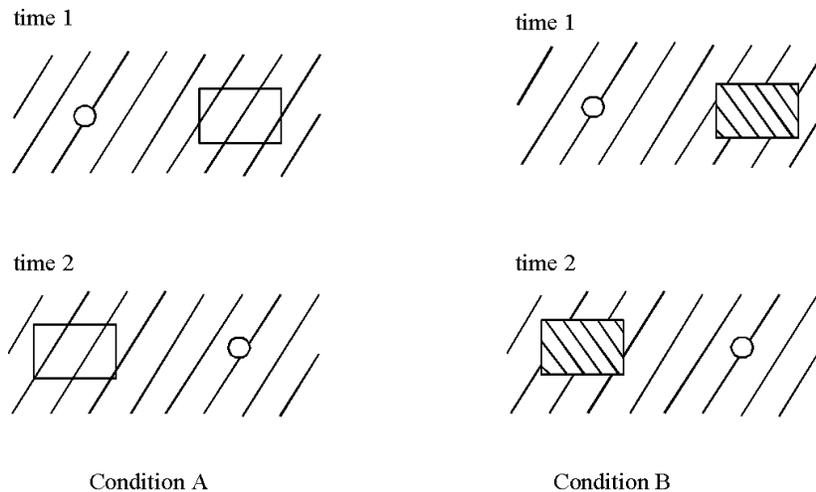


Figure 3-12. In the left figure (A), the texture seen through the rectangle makes it appear to be an outline, so apparent motion is perceived, whereas in the figure on the right (B), the distinct texture on the rectangle makes it appear opaque, so apparent motion is not perceived (after Sigman & Rock, 1974).

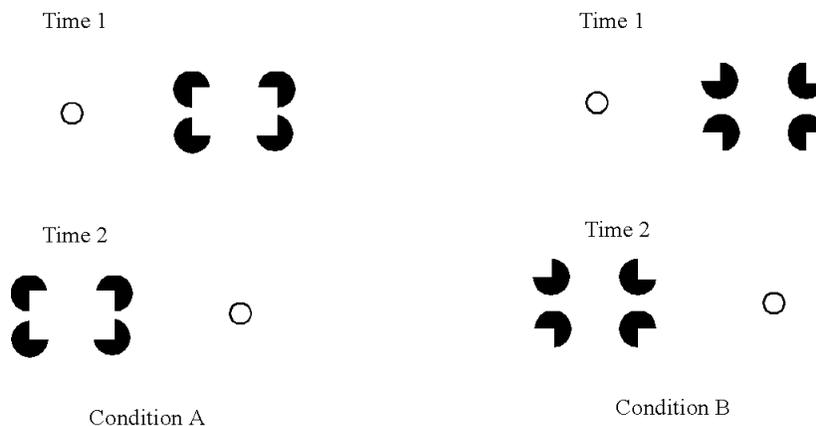


Figure 3-13. In the figure on the left (A), the illusory rectangle appears to be opaque and to alternately cover the two dots so apparent motion is not perceived, whereas in the control display on right (B), apparent motion is perceived (after Sigman & Rock, 1974).

There are many examples showing that the visual system often appears to resolve potential contradictions and inconsistencies in an “intelligent” manner. For example, the familiar illusory Kanizsa figure, such as the rectangle in Figure 3-13A (for other examples, see Kanizsa, 1976) is usually perceived as a number of circles with an opaque (though implicit) figure in front of them that occludes parts of the circles

(the circles with slices cut out of them are often used in illusory contours that form “Kanizsa figures” – they resemble to creatures in the early computer game “Pacman”). The figure is thus seen as closer, brighter, and opaque so that it hides segments of the circles. However, that very same stimulus will not be seen as an illusory figure if a texture is seen through it (as in the figure on the right in Figure 3-14), since this provides counter-evidence to its opacity, and therefore does not explain the missing segments in the three circles.

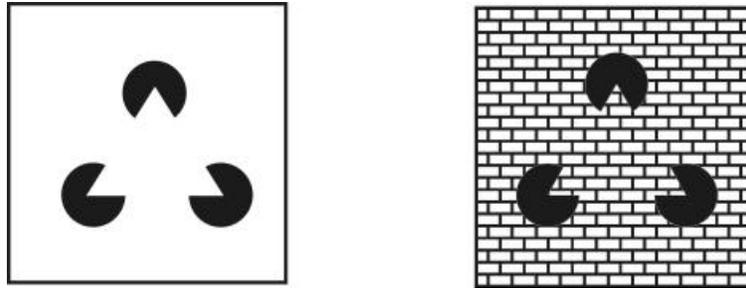


Figure 3-14. A Kanizsa triangle appears vividly in the figure on the left, but is not seen as clearly (is not as stable) if there is conflicting evidence that the triangle is not opaque, as in this case where the background texture apparently can be seen through it.

On the other hand, if the figures are presented stereoscopically or in 3D (with the observer free to move), so that the observer can see that texture is actually in front of the Kanizsa figure, there is no longer a contradiction: subjects see the illusory opaque figure, as it is normally seen, but this time they see it through what appears to be a transparent textured surface (Rock & Anson, 1979). Figure 3-15 shows a schematic of the two situations. Notice that in order for the Kanizsa figure to be seen (as in the situation on the right) the observer has to actually *visually perceive* that the circles with cutouts are on a layer behind the texture. It is not enough that the observer know that this is how they are located in 3D. So that, for example, if the observer has an opportunity to observe the experimental layout by walking around it, and then is forced to look at it monocularly through a peephole (so no depth cues are available – either stereo disparity cues or parallax motion cues) the display will be perceived just as xx is perceived – without the vivid Kanizsa triangle.

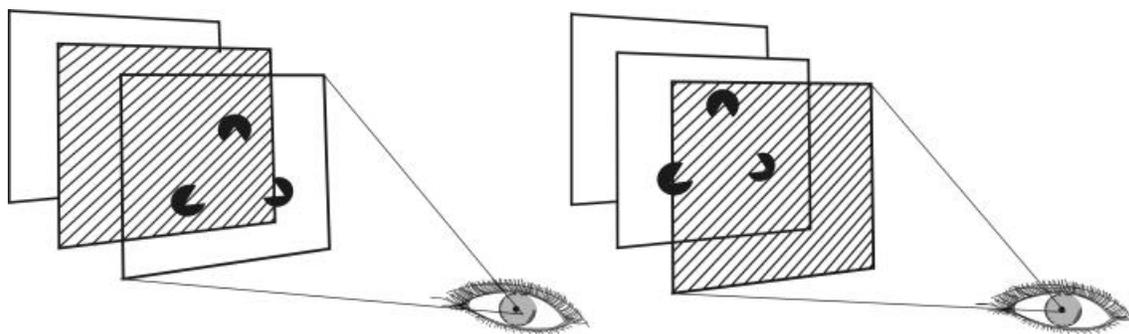


Figure 3-15. Two ways of viewing the figures that make up the situation depicted in Figure 3-14, seen in 3D. The one on the left shows the Kanizsa triangle as being in front of the textured surface (nearest layer is a transparent sheet with a Kanizsa triangle, the next layer is a sheet with textured lines). Since this is incompatible with seeing the triangle as opaque, the triangle is not seen (only the three circles with slices cut out). On the right the viewer sees that the textures surface is in front of the Kanizsa triangle (the closest layer is a transparent texture, the second is the Kanizsa triangle), which does not contradict seeing the triangle as opaque, so the triangle is seen. (Based on Rock & Anson, 1979).

Examples such as these are sometimes interpreted as showing that the way we perceive parts of a scene depends on making some sort of coherent sense of the whole. In the examples cited by Rock, the perception of ambiguous stimuli can usually be interpreted as resolving conflicts in a way that makes sense,

which is why it is referred to as “intelligent”. But what does “making sense” mean if not that our knowledge of the world is being brought to bear in determining the percept?

What distinguishes a function that embodies natural constraints from one that draws inferences from general knowledge, is that (a) the natural constraints do not influence any processes outside of the visual system (e.g., they do not in any way inform the cognitive system); even if one views the visual system as possessing implicit knowledge this knowledge would have to be recognized as special inasmuch as it is not used freely to draw inferences about the world – it is not what (Stich, 1978) calls “inferentially promiscuous”, and (b) the visual process itself does not respond to any other kind of knowledge or new information related to these constraints (e.g., the constraints show up even if the observer knows that there are conditions in a certain scene that render them invalid in that particular case – for example if the observer knew that the texture surface was in front of the Kanizsa triangle it would make no difference to what is seen: Only visually-present information can do that). What this means is that no additional regularities are captured by the hypothesis that the system has knowledge of certain natural laws and takes them into account through “unconscious inferences”. Even though in these examples the visual process appears to be “intelligent” it may be carried out by prewired circuitry that does not access encoded knowledge. Notions such as knowledge, belief, goal and inference give us an explanatory advantage when sets of generalizations can be captured under common principles such as rationality or even something roughly like semantic coherence (Pylyshyn, 1984a). In the absence of such overarching principles, Occam’s Razor or Lloyd Morgan’s Canon dictates that the simpler or lower-level hypothesis (and the less powerful mechanism) is preferred. This is also the argument advanced by (Kanizsa, 1985).

3.1.3 Constraints do not reflect high-frequency or physically permissible real-world principles

Are natural constraints just a reflection of what we frequently see, or of what is possible in the world? Given the empiricist tradition that has colored the past half century of psychology and biology, one might expect this to be so. But it turns out, perhaps surprisingly, that the constraints embodied in vision are not ones characterized in terms of the frequency of their occurrence in the world. The visual constraints that have been discovered so far are based almost entirely on principles that derive from laws of optics and projective geometry. Properties such as the occlusion of features by surfaces closer to the viewer are among the most prominent in these principles, as are principles that are attributable to reflectance, opacity and rigidity of bodies. What is perhaps surprising is that other properties of our world – about which our intuitions are equally strong – do not appear to share this special status in the early vision system. In particular the resolution of perceptual conflicts are rarely resolved so as to respect such physical principles as that solid objects do not pass through one another. Consequently some percepts constructed by the visual system fail a simple test of rationality or of coherence with certain basic facts about the world known to every observer.

Take the example of the Ames trapezoidal window which, when rotated, appears to oscillate rather than rotate through a full circle. When a rigid rod is placed inside this window (at right angles to the frame) and the window-and-rod combination is rotated, an anomalous percept appears. The trapezoidal window continues to be perceived as oscillating while the rod is seen to rotate – resulting in the rod being seen as passing through the rigid frame. (Figure 3-16).

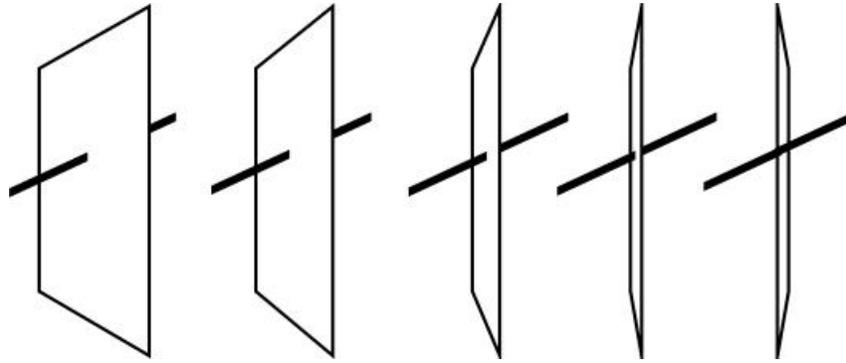


Figure 3-16. When a trapezoidal window rotates about a vertical axis it is seen as swinging back and forth about that axis. When a rod is placed through it, the rod is not subject to this illusion, so it is seen to rotate. As a result at certain points it is seen to penetrate the solid frame.

Another example of this phenomenon is the Pulfrich double pendulum illusion (Wilson & Robinson, 1986). In this illusion two solid pendulums constructed from sand-filled detergent bottles and suspended by rigid metal rods swing in opposite phase, one slightly behind the other. When viewed with a neutral density filter over one eye (which results in slower visual processing in that eye) one pendulum is seen as swinging in an ellipse while the other one is seen as following it around, also in an ellipse but lagging behind. As a result of these distinct trajectories the rigid rods are seen as passing *through* one another. From a certain angle of view the bottles also appear to pass through one another even though they also appear to be solid and opaque. Interpenetrability of solid opaque objects does not seem to be blocked by the visual system, even though it is clearly at variance with what we know about how things inevitably happen in the world.

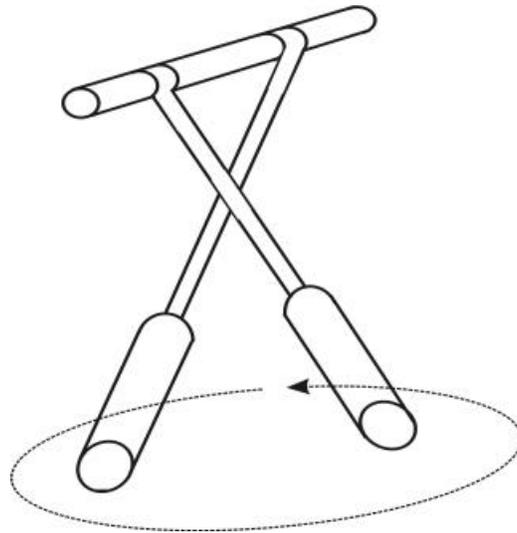


Figure 3-17. The “pulfrich double pendulum”. When viewed binocularly, with one eye looking through a neutral density (gray) filter, the two pendulums appear to swing in an ellipse and out of phase so that one is seen as passing through the other. This and many other examples show that vision does not incorporate physical constraints as obvious as the impenetrability of solid objects.

To repeat the moral of this section: Many cases in which our visual system provides unambiguous (and usually veridical) percepts despite the inherent ambiguity of the 2D image, can be explained without having to assume that the visual system draws inferences from general knowledge regarding what the 3D scene is likely to contain. Although the *beliefs* we come to have about what is in the scene invariably take into account what we know, the output of the early vision system, or to put it loosely (though I believe correctly)

the way things look, does not take into account such knowledge. What the visual is so constructed, presumably because it has become tuned over eons of evolutionary history, that the range of interpretations it is able to make are severely restricted. This range of alternatives is specified by principles (or “rules”) such as the 6 discussed in section 3.1.1.2 (and others discussed by Hoffman, 1998; Marr, 1982; Richards, 1980). These principles are invariably associated with spatio-temporal and optical properties, rather than with physical properties. Consequently they do not appear to just reflect high-frequency properties of the world we live in so much as those critical spatial properties that all animals need in order to survive as mobile agents.

3.2 What is computed by the encapsulated early vision system?

The last chapter argued that the essential, or uniquely visual, part of the visual system, called “early vision,” is isolated from the rest of the cognitive mind. As a consequence, cognition has only two loci of potential control over what we see. These are in *attentional selection* that occurs before early vision, and in *interpretation and memory-based recognition* that occurs after early vision. The latter may also include a cognitively mediated post-perceptual selection. According to this proposal, the visual system may generate several logically-possible interpretations and the alternative that best fits with the system of beliefs and expectations may be selected as the most plausible interpretation, with the others decaying rapidly in time.²¹ While I have defended the claim that early vision is isolated from thought, I have said very little about what goes on within this encapsulated visual system. If what is encapsulated ends up being simple sensory transduction – the conversion of light patterns on the retina to neural patterns on a one-to-one basis – then the thesis that this part of vision is cognitively impenetrable is not very surprising nor very interesting: Few people believe that the rods and cones of the retina and their immediate successors (e.g., the cells with limited retinal receptive fields) are subject to direct control by the cognitive system. What would be more interesting – and what was implied by the discussion in the last chapter – is that the encapsulated function is much more complex and covers much more of the total process that we call visual perception than was generally believed (at least by the psychologists of the past half-century). Indeed, the implication of the last chapter is that the early vision system starts at the point where focal attention zeroes in on relevant aspects of the scene and extends to construct the sort of percept that we might have of a totally unfamiliar scene. For example, I assume that early vision would allow you to make out the individual objects and the spatial layout of a totally unfamiliar scene, such as the landscape of an alien planet where nothing is recognized as familiar. Thus the question of what constitutes the inputs and outputs of the visual system, or what mathematical function is computed by the visual system, are thus of paramount importance to understanding how vision works.

So far I have also said nothing about the nature of the processes that go on within vision, except that they are not what would normally be called *inference*,²² at least not of the sort that is carried out in cognition where there are no principled restrictions on what knowledge can be brought to bear. It is important to see that even though the processes of vision are distinct from the processes of reasoning, they are nonetheless highly structured and made up of distinct stages and submodules. These stages may generate intermediate representations in the course of computing the final form of output. Some of these representations are sufficiently rich and sufficiently different from one another that many vision scientists have suggested that there may be more than one distinct visual system. In the following sections, the nature of the early visual system will be addressed in somewhat greater detail, beginning with a consideration of its inputs and outputs, and then examining the various subprocesses that make it up.

²¹ This sort of process has been proposed for language understanding, where the language-specific syntactical module provides several simultaneous analyses from which the most plausible is selected (see. for example, Swinney, 1979).

²² This is, in part, a terminological point. There are those (e.g., Fodor, 1983; Fodor & Pylyshyn, 1981) who refer to any process that constructs a representation that goes beyond what is in the incoming information as an inference (although it is no easy matter to explicate what it means to “go beyond the incoming information”). I prefer to reserve the term inference for a process that is what (Stich, 1978) calls “inferentially promiscuous” – i.e., that is not restricted in a principled way to what information it can use.

3.2.1 What are the inputs to the visual system?

David Marr pointed out rather forcefully (Marr, 1982), that in order to understand vision we need to first understand what function the visual system computes. For Marr this meant not only specifying the input-output function (in the mathematical sense – i.e., what function it computes), but also how computing that function, rather than some other, supports the organism's needs. For Marr this meant analyzing the visual function in terms of what it was for. One need not accept the tenet that vision needs to be analyzed in terms of some teleological specifications in order to recognize the need to characterize vision in terms of more general functions of an organism. Indeed, this is implicit in the above discussion about natural constraints. But in characterizing the function computed by the visual system we need to be concerned with what exactly constitutes the input to this system. A number of radically different approaches to understanding vision, such as the approach taken by Gibson (Gibson, 1979) and by newer variants of the Gibsonian program (e.g., O'Regan & Noë, 2002), have taken as their point of departure the claim that traditional vision science has misconstrued the nature of the input to vision. In this section I will only sketch these approaches in the most cursory manner (for a more thorough treatment the reader is invited to read Fodor & Pylyshyn, 1981; Pylyshyn, 1984a). However, the question of what constitutes the proper input and output of vision is important because it has a direct bearing on the thesis that vision is independent of cognition (the “modularity of vision” thesis). If we do not constrain what is to count as the input or the output of visual processing we will find that vision includes all of cognition, and the study of vision can become intractable.

When we talk of the visual system, it is obvious that in the first instance we are referring to the system that interprets information coming in through the eyes. It is the system that starts with optical information and eventually produces either the phenomenological experience of seeing, or some relevant observable consequences, such as visually guided action or visual memories or some of the objective psychophysical observations that we alluded to earlier (e.g., those discussed in chapter 1). There are many reasons to believe that information other than optical stimulation to the two retinas may have some role to play in vision. Several different types of input to the visual system have been proposed. One kind of input comes from other sensory modalities, or from sense organs other than the retina. We will briefly survey some of these extra-retinal influences below. They include not only the modulation of vision by such related modalities as the vestibular system and signals from the head and neck muscles, but also information from audition, all of which may play a role in the perception of such properties as spatial location and orientation.

Some researchers have also pointed to the fact of *synesthesia*, in which information coming in from one modality is experienced in a different modality (such as when people experience sounds as different colors) as showing that the visual system can, under certain conditions, be stimulated by nonvisual inputs. We will touch on this sort of evidence briefly below, primarily to ask whether it threatens the thesis that early vision is an independent encapsulated system.

A more problematic proposal has been the widely held view that the input to the visual system can also include what are called “mental images,” or visual information retrieved from memory or generated as a consequence of certain problem-solving activities (e.g., reasoning with the aid of mental imagery). Although it is not inconceivable that an encapsulated visual system might take pictorial inputs generated by cognition, I will later argue that the evidence suggests that this does not in fact take place in the human mind/brain. The case against the view that cognition generates pictures to which the mechanisms of the visual system can be directed will be discussed in the last third of this book. Suffice it to say at this point that the proposal is fraught with difficulties, both conceptual and empirical. The notion of a “pictorial” form of representation which “depicts” rather than “describes” is so ill-defined as to make the question difficult, if not impossible, to answer. Moreover, the strong intuition that invites one to think that there are “pictures” in the mind, which the “mind’s eye” can examine, is illusory, just as the parallel case of postulating mental pictures in visual perception was found to be illusory (as argued in Chapter 1).

3.2.1.1 Cross-modal visual processing

There is some evidence that information from other modalities can modulate vision in systematic ways even early along the visual pathway. For example, inputs from vestibular system appear to affect the perception of orientation, and proprioceptive and efferent signals from the eye and head can effect perception of visual location (Howard, 1982). These findings suggest that certain kinds of spatial information may have an effect across modalities and therefore that in certain cases non-optical sources of information may have to be included among “visual” inputs. Most of these cases concern spatial location, where there is even evidence that acoustical information may affect where objects are visually perceived to be located. Various sources of evidence (e.g., Radeau, 1994) suggest that perceived location may be determined by a fusion of information from several senses, with vision contributing an important share. Whether this a case of fusion of post-visual information or a modulation of vision itself does not affect the principle of dissociation of vision and cognition, though it does affect whether we view, say, certain proprioceptive information from the eye muscles as constituting visual input. There is no *a priori* requirement that visual input consist only of information from the eyes, though that is certainly the prototypical form of input.

There are other sources of evidence of cross-modal influences on visual perception. For example, the perception of certain aspects of speech can be affected by vision and vice versa. For example, it appears that when the input concerns speech, what we see and what we hear both form part of the input to an encapsulated speech perception system. Interestingly, it appears that this applies both to the recognition of the phonetic shape of the signal and also to its location in space (for an extensive discussion see Radeau, 1994, and the commentaries published with it).

There is evidence to suggest that the domain of visual perception may not be coextensive with a single sensory modality. There is also intriguing evidence that the visual system itself may be taxonomized longitudinally, as an encapsulated process that runs from the sensors through to some specific motor subsystems – and consequently that in certain cases the module should be viewed as a *visual-motor* (or *visuomotor*), rather than a strictly *visual* system. This evidence (which has been persuasively presented by Goodale, 1988; Milner & Goodale, 1995) comes from neuroanatomy, from clinical reports of patients with visual agnosias and related neurological deficits, from psychophysical studies of perceptual-motor coordination, and from studies of animal behavior. We review this evidence in section 3.4 below when we discuss the general question of what the visual system outputs to the rest of the mind/brain.

3.2.1.2 Synesthesia: Cross-Modal perception?

It has long been reported that some people experience sensations that they identify as belonging to one modality, say color sensations, when they are in fact being stimulated by a different modality, say by sounds. Such phenomena are known as synesthesia.

Some writers (e.g., Baron-Cohen, Harrison, Goldstein, & Wyke, 1993) have taken the existence of the phenomenon of synesthesia to suggest that vision may not be encapsulated as I have claimed. These writers feel that synesthesia shows that the visual system can sometimes be rather indiscriminate as to where it gets its inputs from since there are cases where the input appears to come from other sensors in other modalities. But the fact that color sensations can be triggered by sound (or sound sensations by touch) does not imply that vision itself, or what we have been calling the early vision system, can take its inputs from sound or other sensory receptors. The reason that the existence of synesthesia does not imply the failure of the boundary of visual perception is of some interest since it helps to clarify what we mean by the “visual system”.

A variety of cases of synesthesia have been examined in recent reviews. These include reviews of both case-studies (Cytowic, 1989, 1993) and experimental studies (Baron-Cohen & Harrison, 1997). The following facts about synesthesia are relevant to its implication for understanding the boundaries of the visual system:

- The cross-modal sensations in synesthesia are not true percepts in a number of respects. Cytowic (1997) describes such sensations as being “generic” rather than “pictorial”. Even when the generic sensations are perceived as deriving from a source in extra-personal space, the sensations do not displace the perceptual content of the primary modality. Synesthetes do not see notes as colored *instead of* hearing them as forming a melody; rather, they hear the melody and they also have sensations of color. In fact it seems correct to say that what they perceive to be out there in the world is melodies, the perception of which happens to be accompanied by sensations of color. The “perceptions” that they have are very different from both veridical perception *and* from perceptual illusions: people who have synesthetic experiences do not mistake melodies for a sequence of colored objects the way people who may be subject to a visual illusion might mistake the illusion for the true situation.
- The connection of synesthesia with conscious sensation is problematic in several ways. While visual perception may be generally associated with a certain sort of conscious experience, the experience may itself be neither necessary nor sufficient for vision. In general what we have been calling visual perception need not itself be accompanied by *any* conscious sensations or other experiential content. Sometimes visual percepts, in the sense of the term that may be the most relevant to visual science, may not have an experiential content. They may, instead, have other kinds of objectively measurable consequences that signal their presence. Examples of these have been given earlier; they include clinical phenomena in which accurate visually guided action is observed in the absence of visual awareness (the most dramatic of which is the phenomenon referred to as blindsight, in which people report no vision in certain parts of their visual field yet are able to reach for objects in the blind field), experimental cases of subliminal perception (the clinical cases will be discussed in Section 3.4.2). It remains an open question how such cases of visual perception should be treated, but at present it seems at the very least premature to confine vision solely to processes that eventuate in conscious sensations. Conversely, the occurrence of visual experience in and of itself need not always indicate that the visual system is involved. In the case of visual experiences arising from hallucinations, dreams, and direct brain stimulation, it is not obvious that any visual information processing is occurring or even that what we have called the early visual system is directly involved (I will have much more to say about this question in chapters 6, 7 and 8).
- Even if we insisted in stipulating that visual sensations must arise from the visual system, this need only be true of a visual system in its normal mode of operation. If we produced visual sensations by cortical stimulation this may or may not mean that we were stimulating the early visual system as we understand the term in the present discussion. We could in fact be bypassing the visual system and stimulating structures that mediate sensations rather than those that compute visual representations. Similarly, if something like the “sensory leakage” theory of synesthesia (Harrison & Baron-Cohen, 1997) were correct and the phenomena was due to leakage across neural pathways that lead, say, to visual sensations, it would still not necessarily mean that inputs to the visual system itself came from the auditory system.
- There is a great deal we don’t know about where, if anywhere, sensations reside in the brain and it may well be that visual sensations do *not* arise from what many people consider the anatomical counterpart of what I have been calling early vision – cortical area V1 (Crick & Koch, 1995). Indeed there is even doubt that an answer to the question of how (or where) the brain produces conscious experiences, including visual sensations, can be formulated in the vocabulary of contemporary psychology and neuroscience. Our current state of understanding of consciousness is such that we are far from warranted even to assume that sensations are the sorts of things that are “produced” or that “occur” in certain places, since there are good reasons to think that they may not be among the “functional properties” of the mind in the usual sense (i.e., properties that have an information processing role). The question of whether conscious experience must have some “functional” consequences is a deeply perplexing problem that has been explored, with widely differing answers, by (Block, 1995; Block, Flanagan & Guzeldere, 1997; Chalmers, 1996; Dennett & Kinsbourne, 1992; McGinn, 1999; Searle, 1995).

Given all these problems and unknowns it seems prudent not to draw conclusions about how the visual system is functionally organized, based on data from synesthesia or other conscious contents, despite the fact that visual science must begin with facts about how things look to us.

The message so far is that what constitutes the input to the visual system cannot be prescribed in advance of the development of adequate theories of vision, nor can we appeal to our conscious experience of seeing to tell us whether some input is to count as a *visual* input. Such questions about the fundamental functional taxonomy of the mind can only be answered as the science develops. Similarly, the question of what the visual system delivers as output can also not be prejudged. There is, however, already some interesting evidence bearing on that question, which I take up next.

3.2.1.3 Should “visual input” include actual and potential motor actions?

We saw in section 3.2.1.1 that visual inputs could be modulated by proprioceptive signals. But the effect of motor activity goes beyond just modulating inputs. In fact there are those who equate the content (or even the experience) of vision with the set of possible stimulus-action contingencies (recent statements of this position can be found in O'Regan & Noë, 2002; Thomas, 1999). Such a point of view can be traced to the influential work of J.J. Gibson (Gibson, 1979), who took the position that visual perception is an organism's active responding (or, as he put it, “resonating”) to the information available in its environment, or in the “optic array.” Such information, according to Gibson, did not just impinge on the sensors passively (if it did, our perception would be filled with illusions and ambiguities). Rather, the organism has to actively explore the optic array just as, in the absence of sight, we would have to actively explore a shape using our tactile (or more generally, our haptic) senses. The idea of vision as an *activity* has seen a recent revival, both in vision science and in artificial intelligence. This approach, versions of which are sometimes referred to as “situated vision” or “embedded cognition,” has helped to correct a long-standing failure of vision science (and cognitive science in general) to pay sufficient attention to how cognition and the world share the responsibility for determining intelligent action.

Herb Simon (Simon, 1969) gives the following example of how a cognitive process and the world together determine patterns of behavior. If we observe an ant on a beach from high above, we will see that the ant is executing a very complex path. To explain the path we might be tempted to hypothesize a very complex cognitive process. But the truth is much simpler: the ant is following a very simple algorithm (e.g., keeping at a certain angle to the sun and refraining from climbing any steep slopes) applied to a complex environment of hills and valleys in the sand.²³ So it is with many other cognitive activities, including doing arithmetic and perceiving the world: the environment plays an important and often neglected role. I will have more to say about this concept of situated vision in section 5.3.2.

This perspective raises the question of whether, by describing vision as an active interaction between an organism and an environment we might avoid (or at least finesse) some of the difficult problems discussed in this book. Gibson believed that the difficult problems of explaining visual perception could be avoided if we described the visual function appropriately, which for him meant shunning the vocabulary of optics and instead using a vocabulary closer to perceptual experience and action. For example, instead of describing the inputs to vision in terms of their proximal projections on the retina, he would have us describe them in terms of what things in the world are perceived *as*, such as objects, surfaces, layouts and so on, and what potential actions they are perceived as permitting, which Gibson called their *affordances*. The latter category brings the study of visual perception into closer contact with the action-based approach that has been advocated by those who view the function of perception as being primarily for allowing us to act on the world. While this is a commendable tempering of an overly zealous cognitivism, it runs in the face of much that has been learned about the intentionality of the mental.

²³ This too is an over-simplification. As it turns out, the ant's internal navigation system is much more complex and sophisticated since it has to compute by dead reckoning, which entails measuring distance and time and integrating the component of the vector distance in the intended direction – while at the same time taking into account the movement of the sun over the course of the trip (Gallistel, 1990), a far from trivial bit of computing! Mammals use an even more complex process to get where they want to go (Gallistel, 1994; Gallistel & Cramer, 1996).

It's true that explaining visual perception or other cognitive phenomena entirely on the basis of inferences carried out over mental representations will not do. In Chapter 2 we saw some reasons for rejecting the traditional approach of treating vision as an extension of reasoning, and later, in Chapter 5 (especially section 5.3) we will discuss other reasons why viewing vision solely as the construction of representations has to be augmented. However, there are three essential properties of a cognizing mind that makes representations indispensable. It is beyond the scope of this book to consider these in detail here (they are discussed at length in Pylyshyn, 1984a) so I will only summarize them for reference.

- (1) The equivalence classes of stimuli over which behavioral regularities have to be stated are semantically defined: stimuli (e.g., sentences) that have the same or similar meanings (e.g., are synonyms or paraphrases) or that have similar interpretations, play the same or similar roles in causing behavior.
- (2) Intelligent behavior is largely stimulus independent. You cannot predict the behavior of an intelligent cognizing agent solely by describing its environment (even including its past environments). This point was made so forcefully in Noam Chomsky's review of Skinner's attempt to characterize linguistic behavior in a behaviorist framework (see Chomsky, 1957) that it should never have to be raised again.
- (3) There is no cognitive (informational, as opposed to physical) regularity or rule that cannot be overturned by additional relevant information. Some portion of any intelligent behavior is always *cognitively penetrable*.

These properties are among the reasons why representations are essential for explaining human cognitive behaviors, and therefore why even a sophisticated psychology of perceptual-motor contingency, or a psychology that addresses environmentally-determined behavior in any form, will eventually run into trouble. The active vision position is often presented as the claim that vision should be characterized in terms of its potential for action rather than its role in thought, and that when this is done we find that representations become less important. It's true that what we see is determined to some extent by how we might potentially act towards it and is also determined in part by the sensory-motor contingencies we expect from such potential actions as eye movements (see, for example, O'Regan & Noë, 2002). It has long been known that the way the eye moves provides important information about the shape of objects and contours (e.g., Miller & Festinger, 1977) and even accounts for some illusions (see sections 3.4.1 and 6.5.2). It is also true that if an object has a certain shape, the organism expects certain sensory patterns to hold as the eye moves. If the eye moves and these expectations go unfulfilled, a perceptual discordance results. The discordance can lead to changes in perception, as it does in the case of perceptual adaptation to distorting lenses. All this is true and important. So it is true that vision depends not only on the proximal visual stimulus (i.e., the retinal projection) but also on patterns of perceptual-motor inputs and even on patterns of expectations of these inputs. One can accept this without giving up on the notion that what vision does is construct visual representations which then serve in motor planning and in cognition the way beliefs generally do, by entering into inferences that may or may not lead to plans based on goals (i.e., old fashioned beliefs and desires).

Preparing for action is not the only purpose of vision. Vision is, above all, a way to find out about the world, and there may be very many reasons why an intelligent organism may wish to know about the world, apart from wanting to act upon it. The organism may just be curious (even rats and pigeons will respond for nothing more than the information about when some non-reward-contingent light will come on, and will do so with greater vigor than for food, e.g. Blanchard, 1975). In the case of humans, it is pretty clear that vision can serve many functions including purely aesthetic ones. Indeed, so powerful is the human drive for knowledge for its own sake that it led George Miller to characterize humans as primarily "informavores" (Miller, 1984).

3.2.2 What are the outputs of the visual system?

3.2.2.1 *The visual output: Categories and surface layouts*

The other important question about vision concerns the nature of the output of the early vision system. This is a central issue because the entire point of the independence thesis is to claim that early vision, understood as that modular part of the mind/brain devoted specifically to processing visual information, is both independent and complex – beyond being merely the output of transducers or feature detectors. And indeed, the examples we have been citing all suggest that the visual system so-defined does indeed deliver a rather complex representation of the world to the cognizing mind.

As we saw in chapter 2, the New Look view, as espoused by Bruner (1957), assumed that we perceive in terms of conceptual categories. Thus according to this view, the visual system does not provide us with raw experiences of the visible world, it interprets these experiences in terms of the categories of cognition, which may be learned or culturally determined. Consequently our knowledge and expectation influences what we see by altering what Bruner called the “readiness” or availability of different perceptual categories. Thus the output of vision, according to this view, is categories of experience. It is important to be clear what the discontinuity or independence thesis, set out in Chapter 2, claims about perceptual categorization. The discontinuity thesis does not claim that our readiness and willingness to categorize something in our field of view as an X is independent of our expectation that there are X’s in our field of view. That is because, as I have already noted, what we believe is in our field of view clearly does depend on such factors as our prior beliefs, as it should if you are a rational agent. Nor does the discontinuity thesis claim that the visual system does not divide the world up into equivalence classes, which is another way of saying that it divides it into some kinds of categories. The fact that the mapping from the distal 3D environment to a percept is many-one entails that the visual system fails to distinguish certain differences. Another way of saying this is that by collapsing certain differences, the visual system partitions the visual world into “equivalence classes”. But these kinds of classes are not what Bruner and others meant when they spoke of the categories of visual perception. The perceptual classes induced by early vision are not the kinds of classes that are the basis for the supposed enhancing effect of set and expectations. They do not, for example, correspond to meaningful categories in terms of which objects are identified when we talk about perceiving as, e.g., perceiving something as a face or as Mary’s face and so on. To a first approximation the classes provided by the visual system are shape-classes, expressible in something like the vocabulary of geometry.

Notice that the early visual system does not *identify* the stimulus, in the sense of cross-referencing it to the perceiver’s knowledge base, the way a unique inner label (e.g., “the girl next door”, or “my car”), might. That is because this sort of identity or labeling is inextricably linked to past encounters and to what one knows about members of the category (e.g., what properties – both visual and nonvisual – they have). After all, identifying some visual stimulus as your sister does depend on knowing such things as that you have a sister, what she looks like, whether she recently dyed her hair, and so on. But, according to the view I have been advocating, computing what the stimulus before you looks like – in the sense of computing some representation of its shape sufficient to pick out the class of similar-appearances,²⁴ and hence to serve as an index into visual memory – does not itself depend on knowledge.

So far I have spoken only in very general terms about the nature of the stimulus classes picked out by vision. These classes could well be coextensive with basic-level categories (in the sense of, Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976), but the visual system itself does not label the output in terms of the

²⁴ The question of what constitutes “similarity of appearance” is being completely begged in this discussion – as is the related question of what makes some things appear more similar than others. We simply assume that the capacity or establish something like similar-in-appearance is given by our cognitive architecture – i.e. that it is built in to the nervous system. Whether it is explicitly recognized or not, every theory of vision (and of concepts, see Fodor, 1998) assumes such a capacity. Objects that are “similar” in appearance are typically taken to be ones that receive similar (or in some sense “overlapping”) representations in the output of the visual system. This much should not be problematic since, as I remarked earlier, the output necessarily induces an equivalence class of stimuli and this is at least in some rough sense a class of “similar” shapes.

name of the category, for reasons already alluded to above. It also seems reasonable that the shape-classes provided by vision are ones whose names could be learned by ostension – i.e., by pointing or holding up an example of the named thing, rather than by providing a description or definition. Whether or not the visual system actually parses the world in these ways (i.e., into basic-level categories) is an interesting question, but one that is beyond the scope of this book. I have also not said anything about the form and content of the output beyond the claim that it contains shape-classes. I will return to this issue below.

For the time being we have the very general proposal that the visual system might be viewed as generating a set of one or more shape-descriptors which in many cases might be sufficient (perhaps in concert with other contextual information) to identify objects whose shapes are stored in memory – presumably along with other information about these objects. This provisional proposal is put forward to try to build a bridge between what the visual system delivers, which, as we have seen, cannot itself be the identity of objects, and what is stored in memory that enables identification. Whatever the details of such a bridge turn out to be, I still have not addressed the question of how complex or detailed or articulated this output is. Nor have I addressed the interesting question of whether there is more than one form of output; that is, whether the output of the visual system can be viewed as unitary or whether it might provide different outputs for different purposes or to different parts of the mind/brain. I will return to this idea, which is related to the “two visual systems” hypothesis, below.

The precise nature of the output in specific cases is an empirical issue that we cannot prejudge. There is a great deal that is unknown about the output: For example, whether it consists of a combinatorial structure that distinguishes individual objects and object-parts or whether it encodes non-visual properties, such as causal relations, or primitive affective properties like “dangerous”, or even some of the functional properties that Gibson referred to as “affordances”. There is no reason why the visual system could not encode any property whose identification does not require accessing general memory, and in particular that does not require inference from general knowledge. So, for example, it is possible in principle for overlearned patterns – even patterns such as printed words – to be recognized from a finite table of pattern information compiled into the visual system. Whether or not any particular hypothesis is supported remains an open empirical question.²⁵

Although there is much we don’t know about the output of the visual system, we can make some general statements based on available evidence. We already have in hand a number of theories and confirming evidence for the knowledge-independent derivation of a three-dimensional representation of visible surfaces – what David Marr called the 2.5-D sketch (since a full 3D representation would also contain information about the unseen back portion of objects). Evidence provided by J.J. Gibson, from a very different perspective, also suggests that what he called the “layout” of the scene, may be something that the visual system encodes (Gibson would say “picks up”) without benefit of knowledge and reasoning. (Nakayama, He & Shimojo, 1995) have also argued that the primary output of the independent visual system is a layout of surfaces laid in depth. Their data show persuasively that many visual phenomena are predicated on the prior derivation of a surface representation. These surface representations also serve to induce the perception of the edges that delineate and “belong to” those surfaces. Nakayama et al. argue that because of the prevalence of occlusions in our world it behooves any visual animal to solve the surface-occlusion problem as quickly and efficiently and as early as possible in the visual analysis and that this is done by first deriving the surfaces in the scene and their relative depth.

Nakayama et al. were able to show that the representation of surfaces in depth, and therefore the occlusion relations among surfaces (i.e., which one is partially behind which) is encoded in the

²⁵ One of the useful consequences of recent work on connectionist architectures has been to show that perhaps more cognitive functions than had been expected might be accomplished by table-lookup, rather than by computation. (Newell, 1990) was one of the cognitive scientists to recognize early on the important tradeoff between computing and storage that a cognitive system has to face. In the case of the early vision system, where speed takes precedence over generality (see, for example, Fodor, 1983), this could take the form of storing a forms-table or set of templates in a special intra-system memory. Indeed, we have already suggested that this sort of compiling of a local shape-table may be involved in some perceptual learning and in the acquisition of visual expertise.

representation very early – in fact even before shapes have been derived. The priority of surface derivation over the derivation of other features of a scene was shown by placing information about edges and shapes in conflict with information about relative distances of surfaces from the viewer. The demonstrations are very impressive, but unfortunately they require that displays be presented as stereographic images in order to provide the depth information independently of the other form information. Without a stereoscope many people find it difficult to obtain a stereo effect from a printed page. Doing so requires “free fusing” and it can be achieved with some patience.²⁶ The results can be spectacular!

Consider the display shown in Figure 3-18. It consists of what appear to be **I**'s and **L**'s. In a two-dimensional display the **I**'s form a cluster and tend to “pop out” as a distinct region. If the figure is fused so it appears three-dimensional, the dotted regions appear in front of or behind the white regions. (He & Nakayama, 1994) showed that the outcome of the clustering process depends on the prior computation of depth and of occlusion. The two rows of Figure 3-18 show the two alternatives. If the **L**s and **I**s are seen as *in front of* the dotted region, then we get the expected easy popout of the region of **I**s from the region of **L**s. But if the **I**s and **L**s are seen as *behind* the dotted regions, the visual system interprets them as the visible parts of a white square – so we see a field of squares partly occluded by the dotted regions, rather than a field of distinct **I**s and **L**s. These alternative perceptions of the elements of Figure 3-18 are illustrated in Figure 3-19 for clarity. Because texture segregation is known to be computed at a very early stage in vision – in fact a typical operation of early vision – this shows that early vision takes into account not only depth but, more importantly, the occlusion relation among surfaces and that therefore that such information is implicit in the output of the early vision system.

²⁶ To achieve the stereo effect, try one of the following two methods (one is called parallel- and the other crossed-fusion). For parallel fusion, bring the figure up close to your face and try staring *through* the page into the distance (let your eyes go out of focus at first). Then back the page away while watching the pair on the right until the plus signs merge (the X pairs are for crossed fusion and the U pairs are for uncrossed fusion). For crossed fusion it is better to start with the page further away and to look at a pencil placed about halfway between the eyes and the page. Look at the pencil and line it up with some feature of the pair of figures on the left side of the display. With practice you will be rewarded with the sudden appearance of the clear impression of depth in these pictures.

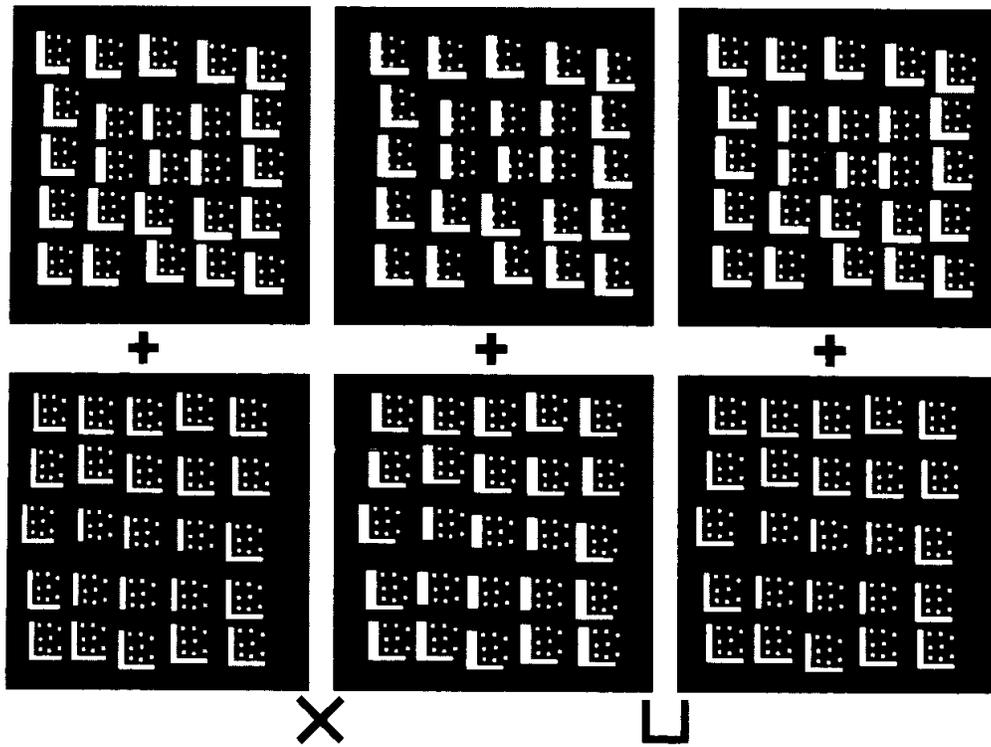


Figure 3-18. When properly fused, the top rows show the L and I elements as being in front (so they are represented as actual I's and L's would be). In the bottom row the white elements are seen as being in back of the dotted figures, so they all look like partially-occluded squares. In the top row the I elements pop out from among the Ls and form a cluster, while in bottom example, the clustering has to be done deliberately and with difficulty. This shows that the automatic pre-attentive clustering process makes use of the result of the depth and occlusion-computation. (Reprinted from He & Nakayama, 1994)

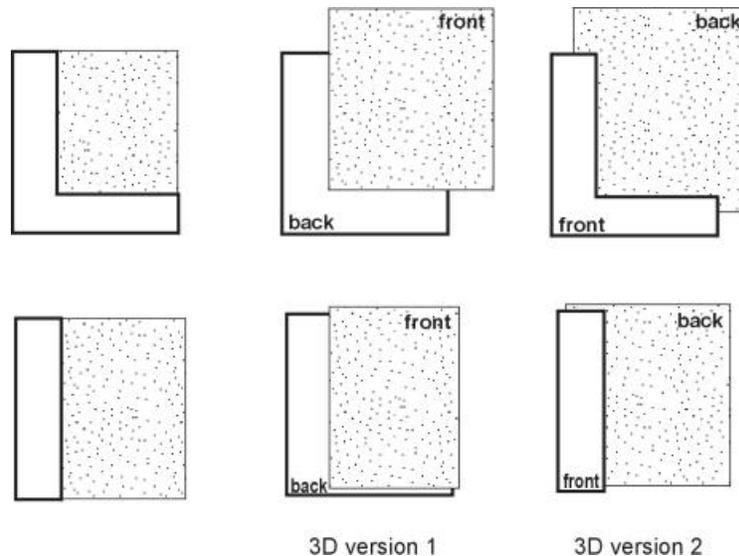


Figure 3-19. This helps to visualize how the Individual elements of Figure 3-18 are perceived as either **I**s or **L**s, depending on the perceived depth of the white and dotted regions. This figure shows how the items are seen in depth: in version 1 the white regions are seen as behind and so are visually completed as squares, while in version 2 the white regions are seen as in front so are perceived as **I** or **L**.

The evidence generally favors the view that some depth-encoded surface representation of the layout is present in the output of the early-vision system. The evidence also shows that the representation is not complete and uniform in detail – like an extended picture – and that intermediate representations are computed as well. I have already devoted considerable attention to the first of these in Chapter 1 and have argued that the visual system certainly does not generate a complete picture-like representation in the mind. With regard to the intermediate-representation issue, there is evidence that several types and levels of representation are being computed, yet there is no evidence that these interlevels and outputs of specialized subprocesses are available to cognition in the normal course of perception. So far the available evidence suggests that the visual system is not only cognitively impenetrable, but is also opaque with respect to the intermediate products of its process (see 3.3).

A phenomenon that may illustrate the opacity of early visual processes is called the “word superiority effect.” It has been shown that it is faster to recognize whole words than individual letters, even when deciding which word it is requires having recognized the individual letters. For example, it is faster to distinguish **WORD** from **WORK**, than it is to distinguish the individual letter **D** from the letter **K**, despite the fact that differentiating **WORD** from **WORK** logically requires differentiating a **D** from a **K**. One possible explanation is that the **D** (or **K**) is recognized early in the word recognition case but the information is not made available to the cognitive system directly, but it is made available to the word-recognition system, which can then respond with the correct word and can also infer (after some delay) that there was a **D** (or **K**) present. This is even clearer in the case of phonemes that must be used to make linguistic distinctions. Yet it requires special training to be able to detect the presence of the particular phone in speech (which is why making phonetic transcriptions of foreign language – even one that uses the same sounds as your own – is very difficult). It may be that a representation of a letter or phoneme is computed but the intermediate representation is not available except to the word recognition system, and therefore can only be inferred from knowing what word that was spoken or written.

In commenting on my paper in *Behavioral and Brain Sciences*, in which I argue for the impenetrability of early vision, (Hollingworth & Henderson, 1999) suggest that a “presemantic” match between memory and the description generated in the course of early vision may take place within early vision itself, allowing access to information about the object type. They base this proposal on the finding that when you control for the effect that context might have in focusing attention to certain locations, recognizing an object is not

aided by the semantic congruence between the object and its scene context – it is just as easy to recognize a toaster or a chicken whether they are shown as being in a kitchen or in a farmyard (see, Hollingworth & Henderson, in press). Since semantic congruity does not help recognition cannot itself be mediated by semantic factors or by such semantically-sensitive processes as reasoning. However, this result is compatible (as Hollingworth & Henderson recognize) with the idea that the early vision system simply outputs what I have called a canonical shape or shape-category (which I assume is very close to their notion of “presemantic” recognition). On the other hand, as I have argued, such a presemantic categorization need not involve matching anything to memory – it could simply be the structured description corresponding to an equivalence class induced by early vision. Of course to recognize this class (which might have the internal name, say, Q374) *as* a toaster (with all that this implies about its functional and conventional properties) *does* require making contact with a knowledge base, which requires not only lookup but perhaps also various inferences (e.g., that it is usually found on the kitchen counter) and therefore this sort of recognition lies outside the province of early vision. So I agree with Hollingworth and Henderson’s proposal but do not see it as requiring memory lookup except when it is associated with a judgment such as, for example, that the object is something that has been seen before or that it has a certain name. Once an appropriate canonical shape-description is constructed it may be a relatively simple matter to match it to a knowledge base of names. In fact what the Hollingworth and Henderson experiments show is that the step between achieving the shape-description and locating its name is, at least in the case of simple objects, fast and direct and not enhanced by semantic congruence or degraded by semantic incongruence of the context.

One important question concerning visual processing that has not yet been explicitly addressed is the question of whether vision is a single uniform process or whether it consists of distinct subprocesses – or even whether there are distinct visual systems that operate in parallel or in different contexts. I have suggested that there are stages in visual processing – for example the stage of computing depth precedes the stage at which shape is computed. The question of stages is also raised by a wide range of evidence suggesting that what is available to phenomenal experience may not be what is available to other processes. There is also strong evidence that the ability to make visual discriminations, to localize and to combine visual properties, and to recognize familiar objects, can be dissociated from the ability to act on the basis of visual information. These issues are discussed below.

3.3 Some subprocesses of the visual system

I have already suggested several ways in which the phenomenology of vision is seriously misleading. Another misleading impression is that vision happens suddenly, with little intervening processing. The experience of seeing appears to be so automatic and almost instantaneous that it is hard to believe that there may be different subprocesses involved, or that the visual system might inform different parts of the mind-brain in different ways or about different things. Like the phenomenological impression of an inner screen, the phenomenological impression we have is that of a unitary and virtually instantaneous process. But these impressions, too, are far from providing a valid characterization of what goes on in vision.

An important class of evidence from human psychophysics shows that vision is far from being an undifferentiated monolithic process. For example, there is evidence of intermediate stages in the computation of a depth representation. Indeed the time-course of some of the processing has been charted (e.g., Calis, Sterenborg & Maarse, 1984; Reynolds, 1981; Schulz, 1991; Sekuler & Palmer, 1992) and there are computational reasons why earlier stages may be required. For example, Marr’s analysis of early vision has room for at least a retinotopic representation called the raw Primal Sketch, as well as a Full Primal Sketch which groups together related edge-detector results, and labels edges as to how sharp they are and so on, before producing a 2.5D representation and then finally an object-centered representation. Also there is now considerable evidence from both psychophysics and from clinical studies that the visual system consists in a number of separate subprocesses that compute color, luminance, motion, form and 3-D depth and that these subprocesses are restricted in their intercommunication (Cavanagh, 1988; Livingstone & Hubel, 1987). In other words, the visual process is highly complex and articulated and there are intermediate stages

in the computation of the percept during which various information is available in highly restricted ways to certain specific subprocesses.

Other evidence suggests that there are severe restrictions on the flow of information among the many subsystems involved in visual perception. Indeed the factoring apart of cognition and vision, with which I have been concerned in the previous chapter, turns out to be an instance of a general property of many parts of the cognitive system. The partitioning of the cognitive system into subsystems is quite common and extends to many functions within vision itself. For example, there appear to be subsystems within the visual process that result in restricted access to either general world knowledge or to the outputs of their sister systems. Conversely many of these subsystems do not provide information to the general cognitive system, but only to specific subsystems, such as certain motor subsystems. For example, the visual system appears to make certain information available to the motor system subserving reaching and grasping, but not to the general cognitive system. The visual system also appears to process some classes of features (e.g. color) independently of other classes (e.g. motion), and so on.

An impressive demonstration of this is to watch a display of moving blue/yellow or red/green bars (or sine-wave gratings), while the relative luminance of the pairs of colors is varied (so that the red becomes more/less bright). As the luminance of the two colors approaches subjective equality the perceived speed of motion slows down and may even drop to zero, *despite the fact that you can clearly see that over time the gratings are in successively different locations!* Perceived speed of motion, it seems, is sensitive to luminance and much less to color information even though the color information is sufficient to allow you to see where the gratings are. Similarly it has been argued (but also contested) that luminance information alone does not contribute to stereo— at least in the case of nonfigural (random dot) stereograms. There is also evidence suggesting that color and luminance function differently in determining the perception of size and orientation.

Perhaps even more interesting are the findings concerning the role of different early analyzers in determining three dimensional form percepts. In particular, when luminance or color or texture provides the sole input, the visual system may construct different percepts—even when the information is the same on a local basis (i.e., when the information defines the same 2D contours). For example, Figure 3-20 shows that if information is provided in terms of luminance differences then certain contours may be interpreted as shadows and the implicit outlines of the objects as well as the surface relief may be reconstructed, whereas the same does not occur when the contours are presented by equiluminant contrasts (e.g. equiluminant textures, as show here, or color, relative motion or binocular disparity). Figure 3-21 shows that information based on luminance contrast can allow the construction of so-called `subjective contours' whereas the same information provided without luminance contrast does not. These examples show that information that is in some sense the same (e.g. defines the same local features or the same contours) but which arises from different analyzers at one stage in the visual process may nonetheless not be interpreted the same way by the next stage in perceptual process. In other words certain analyzers at stage n may not feed information to analyzers at stage $n+1$ even though the equivalent information from a different stage n analyzer *is* used by the stage $n+1$ analyzer.

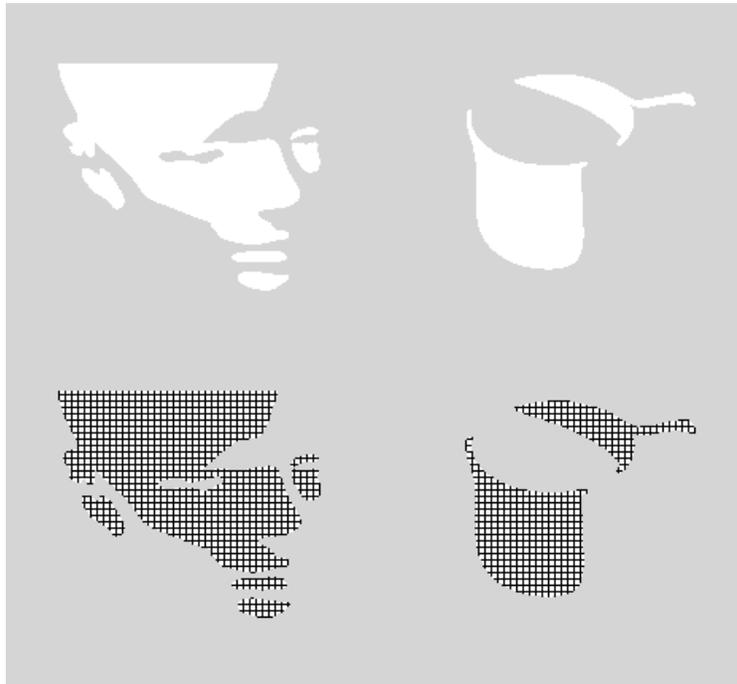


Figure 3-20. Figures with real and shadow contours produced by approximately equiluminous (bottom pair) and non-equiluminous (top pair) regions (From Cavanagh, 1988)

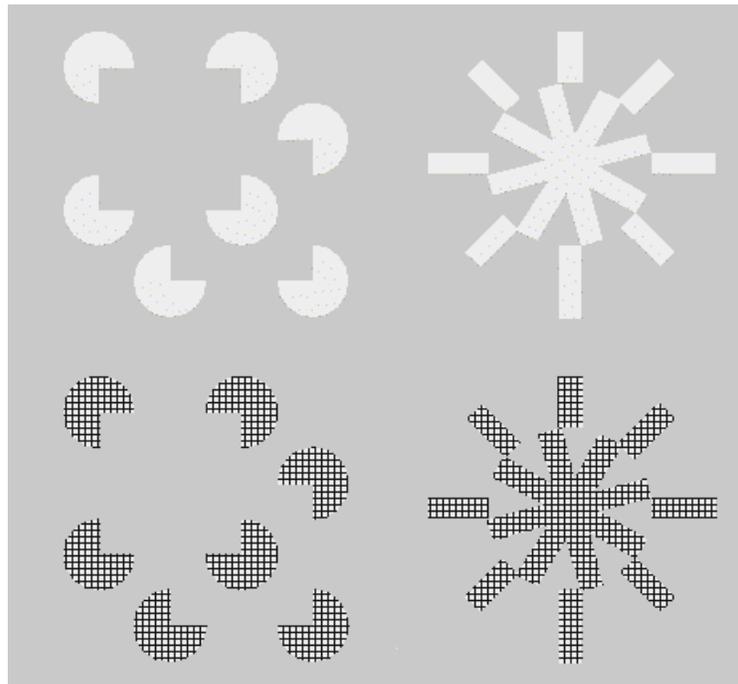


Figure 3-21. Figures with real and subjective contours produced by approximately equiluminous (bottom pair) and non-equiluminous (top pair) regions (From Cavanagh, 1988).

In another series of impressive demonstrations, (Livingstone & Hubel, 1987) showed that depth cues, such as occlusions or converging perspective lines, lose their potency for invoking depth in displays where the cues are presented as color features that are equiluminant with the background. Similarly, figure-ground discrimination and other low-level ‘Gestalt’ phenomena disappear when the image features are presented in

the form of color alone – i.e., as lines or edges with the same luminance as the background. Livingstone & Hubel develop an elegant neurophysiological story, based on the existence of different pathways and different types of neural cells, to go along with these observations, and these help to anchor the taxonomy in biological data. From our perspective, however, we may conclude that there are subsystems in vision that compute their function independent of one another and which communicate the results of their analyses in a restricted manner to each other and to subsequent stages in the analysis. Figure 3-22 shows an example of a flow diagram of visual stages based on such an analysis.

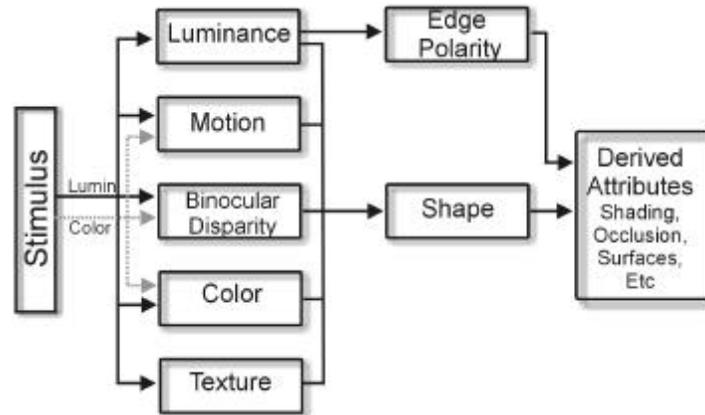


Figure 3-22 Diagram of some of the pathways in early vision, showing that color information feeds into binocular disparity analysis, and to a lesser extent into motion analysis. Shape, as defined by explicit contours, can be determined by any pathway. Yet shape that is defined by implicit contours, can only be determined by the luminance pathway, which, in turn, requires all the edges be of fixed polarity (From Cavanagh, 1988).

3.3.1 Stages in early vision: Microgenesis of vision

I have already discussed the analysis of vision into stages, with attention allocation, early vision, and decision or judgment marking important distinctions within what is informally called vision. We also saw that within early vision, processes such as those that compute color, stereo, contour, motion, and three-dimensional layout have restricted intercommunication among each other and with higher cognitive systems. It also appears that within early vision a percept does not come into being suddenly, sometimes involves a set of operations that are applied in sequence. Although not a great deal is known about such sequences, since they happen rapidly and unconsciously, there is evidence that some perceived properties take more time than others to construct, even when the construction does not involve appeal to memory and knowledge, as for example in the construction of illusory contours or other illusions (Reynolds, 1981; Reynolds, 1978; Schulz, 1991; Sekuler & Palmer, 1992), as well as for higher-order visual processes such as involved in the perception of faces (Bachmann, 1989; Calis et al., 1984; Hagenzieker, van der Heijden & Hagenaar, 1990). Although the stages described in the previous section may take time, I am not aware of any published studies concerning the time-course of these analyses, despite the fact that it is known that some of these stages must precede other stages, as illustrated in Figure 3-22. A few detailed temporal analyses have been carried out, however, and have established the time course of certain operations applied to the visual input, providing evidence for what has become known as the microgenesis of vision.

For example, (Reynolds, 1978) showed that it takes some time for certain illusions to develop, and that the interactions responsible for such illusions as the Ponzo, Zollner and rod-and-frame illusions occur only after about 150 ms of processing time. (Reynolds, 1981) also showed that it takes time for illusory contours to be constructed and that early masking of the stimulus can disrupt this construction.²⁷ For example, Figure 3-23 illustrates that under normal viewing conditions, or with a long interstimulus interval prior to masking, observers do not perceive an illusory triangle because the perceiving the brick-like background is incompatible with perceiving the triangle as opaque – as required in order to see the illusory triangle covering the three black circles. If, however, the circles are masked after only a short interval, the illusory triangle is perceived because the incompatibility does not have time to interact with the perception of the background.

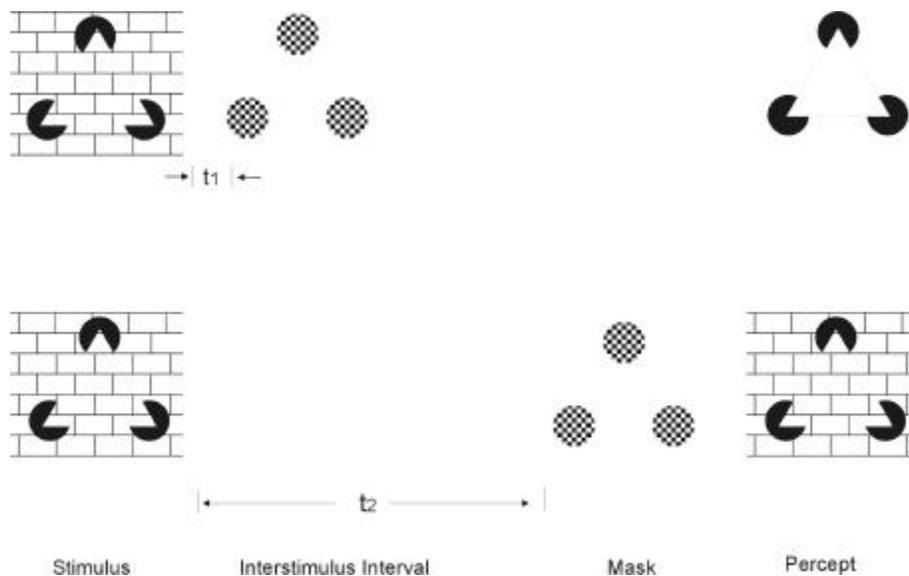


Figure 3-23. When insufficient time is available (top figures, with short ISI), the conflict between two percepts does not emerge and the illusory triangle is perceived (here $t_1 < 150$ ms). (based on Reynolds, 1981).

²⁷ (Parks, 1994) failed to replicate this result and cast some doubt on the experimental procedure used by (Reynolds, 1978). However, (Parks, 1995) subsequently developed a different technique and was able to confirm that construction of different aspects of a percept does indeed take time. In particular, he showed that with increasing time illusory contours such as those of Figure 3-23 can be prevented, whereas when conflicting information is present only briefly the inconsistency is tolerated, as suggested in the original Reynolds study described above.

Using a different experimental paradigm to study the time-course of construction of visual percepts, (Sekuler & Palmer, 1992) sometimes showed observers partially-occluded figures, sometimes the corresponding visible fragments of figures, and sometimes the whole figures, prior to a visual judgment task (the task involved judging whether pairs of figures were identical). A judgment task such as this is speeded up when preceded by a brief exposure to the figure being compared; a phenomenon referred to as visual priming. The priming figures are shown in row (a) of Figure 3-24 while the ones that were actually primed in the subsequent comparison task are shown in row (b). Sekuler and Palmer showed that in such a situation, a partially occluded figure (such as shown in the first column of Figure 3-24) acts more like the completed figure (shown in the second column) than like the figure fragment that is actually present (shown in the third column and fourth columns). For example, presenting the partially occluded circle, such as in the first column of row (a) primes a subsequently presented figure-comparison task involving the circle, just as it would have if the actual circle had been presented (as shown in column 2). However if just the fragment is presented (as in column 3) it will only prime a fragment figure, as shown below it in row (b) – even if the same elements are present, as in the control case shown in column 4. The important additional finding was the completed-figure priming effect (the one shown in the first column) is *only* observed if the occluded figure is viewed for at least 200 ms; otherwise it is the fragment that is primed, and not the whole figure, which is partially hidden behind the occluding surface. It thus appears to take at least 200 ms for the occluded figure to be completed.

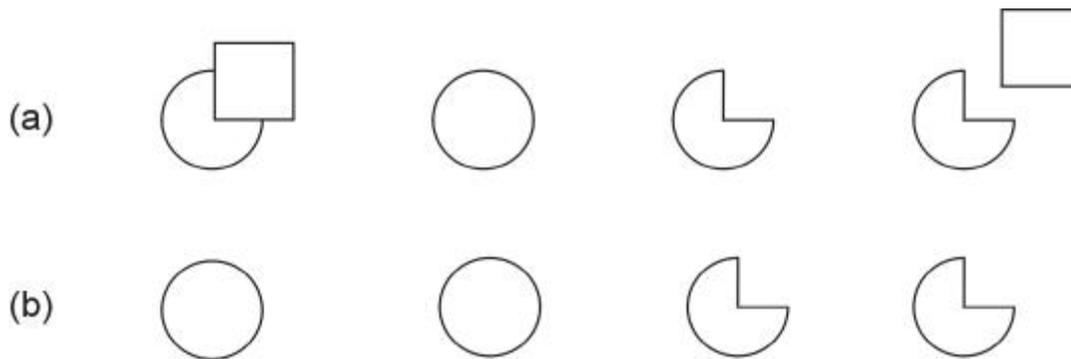


Figure 3-24. When presented with a figure such as in row (a), the effect on a subsequent comparison task is like that of the figure directly below it in row (b), providing that the time between the start of figure (a) and the start of the prime task is at least 200 ms (based on Sekuler & Palmer, 1992).

This study also shows that the phenomenon known as “amodal completion” (discussed in Chapter 1) does not just affect how something appears, but has real consequences for information processing (in this case for priming). Nonetheless, the completion of a figure takes time and before the complete figure has been constructed by the visual system, only the fragment appears to be available for subsequent processing.

3.4 Visual control of action: An encapsulated system?

So far I have been speaking as though the sole purpose of vision is to provide us with knowledge of the world – an important aspect of which is to recognize objects, thereby providing a connection between the current scene and past experience. Vision is indeed the primary way that most organisms come to know the world and such knowledge is important in that it enables behavior to be detached from the immediately present environment. Visual knowledge can be combined with other sources of knowledge for future use through inference, problem-solving and planning. But this is not the only function that vision serves. Vision also provides a means for the immediate control of actions and sometimes does so without informing the rest of the cognitive system – or at least that part of the cognitive system that is responsible for recognizing objects and for issuing explicit reports describing the perceptual world. Whether this means that there is more than one distinct visual system remains an open question. At the present time the evidence is compatible with there being a single system that provides outputs separately to the motor control functions

or to the cognitive functions. Unless it is shown that the actual process is different in the two cases this remains the simplest picture. So far it appears that in both cases the visual system computes shape-descriptions that include sufficient depth information to enable not only recognition, but also reaching and remarkably efficient hand positioning for grasping (Goodale, 1988). The major difference between the information needed in the two cases is that motor-control primarily requires quantitative, egocentrically calibrated spatial information, whereas the cognitive system is concerned more often with more qualitative information and relative with locations (Bridgeman, 1995).

The earliest indications of the fractionation of the output of vision probably came from observations in clinical neurology (e.g., Holmes, 1918), which will be discussed in Section 3.4.2 below. However, it has been known for some time that the visual control of posture and locomotion can make use of visual information that does not appear to be available to the cognitive system in general. For example, (Lee & Lishman, 1975) showed that posture can be controlled by the oscillations of a specially designed room whose walls were suspended inside a real room and could be made to oscillate slowly. Subjects standing in such an “oscillating room” exhibit synchronous swaying even though they are totally unaware of the movements of the walls.

3.4.1 Evidence from studies of eye movements and reaching

The largest body of work showing a dissociation between visual information available to general cognition and information available to a motor function involves studies of the visual control of eye movements as well as the visual control of reaching and grasping. (Bridgeman, 1992) showed a variety of dissociations between the visual information available to the eye movement system and that available to the cognitive system. For example, he showed that if a visual target jumps during an eye movement, and so is undetected, subjects can still accurately point to the correct position of the now-extinguished target. In earlier and closely related experiments, (Goodale, 1988; Goodale, Pelisson & Prablanc, 1986) also showed a dissociation between information that is noticed by a subjects and information to which the motor system responds. In reaching for a target, subjects first make a saccadic eye movement towards the target. If during the saccade the target undergoes a sudden displacement, subjects do not notice the displacement because of saccadic suppression. Nonetheless, the trajectory of their reaching shows that their visual system did register the displacement and the motor system controlling reaching is able to take this into account in an on-line fashion and to make a correction during flight in order to reach the final correct position.

(Wong & Mack, 1981) and subsequently (Bridgeman, 1992) showed that the judgment and motor system can even be given conflicting visual information. The Wong & Mack study involved stroboscopically-induced motion. A target and frame both jumped in the same direction, although the target did not jump as far as the frame. Because of induced motion, the target appeared to jump in the opposite direction to the frame. Wong & Mack found that the saccadic eye movements resulting from subjects' attempts to follow the target were in the actual direction of the target, even though the perceived motion was in the opposite direction (by stabilizing the retinal location of the target the investigators ensured that retinal error could not drive eye movements). But if the response was delayed, the tracking saccade followed the perceived (illusory) direction of movement, showing that the motor-control system could use only immediate visual information. The lack of memory in the visuomotor system has been confirmed in the case of eye movements by (Gnadt, Bracewell & Anderson, 1991) and in the case of reaching and grasping by (Goodale, Jacobson & Keillor, 1994). (Aglioti, DeSouza & Goodale, 1995) also showed that size illusions affected judgments but not prehension (Milner & Goodale, 1995). Another demonstration of the apparent insensitivity of certain illusions to the visuomotor system are some findings concerning the Müller-Lyer illusion. A surprising finding with this illusion is that the location of the endpoints of the lines can be judged very accurately under conditions where the line length shows a strong illusion (Gillam & Chambers, 1985; Mack, Heuer, Villardi, & Chambers, 1985). The apparent dissociation between judgement of position and judgement of length is of particular interest in the present context because the location judgment was provided by a motor gestures while the length judgement was verbal. The location of the endpoints in these cases are indicated by making motor gestures towards the display. In the Gillam & Chambers case it

was indicated by placing a dot under the endpoints and in the Mack et. al. the response involved actually pointing to the endpoint. The pointing was free of bias even when the hand was hidden from view.

3.4.2 Evidence from clinical neurology

Clinical studies of patients with brain damage provided some of the earliest evidence of dissociations of functions which, in turn, led to the beginnings of a taxonomy (and information-flow analyses) of skills. One of the earliest observations of independent subsystems in vision was provided by (Holmes, 1918) who described a gunshot victim who had normal vision as measured by tests of acuity, color discrimination and stereopsis, and had no trouble visually recognizing and distinguishing objects and words. Yet this patient could not reach for objects under visual guidance (though it appears that he could reach for places under tactile guidance). This was the first in a long series of observations suggesting a dissociation between recognition and visually guided action. The recent literature on this dissociation (as studied in clinical cases, as well as in psychophysics and animal laboratories) is reviewed by (Milner & Goodale, 1995).

In a series of careful investigations, (Milner & Goodale, 1995) reported on a remarkable case of visual dissociation. This patient, known as DF, shows a dissociation of vision-for-recognition and vision-for-action, illustrating a clear pattern of restricted communication between early vision and subsequent stages, or to put it in the terms that the authors prefer, a modularization that runs from input to output, segregating one visual pathway (the dorsal pathway) from another (the ventral pathway). DF is seriously disabled in her ability to recognize patterns and even to judge the orientation of simple individual lines. When asked to select a line orientation from a set of alternatives that matched an oblique line in the stimulus, DF's performance was at chance. She was also at chance when asked to indicate the orientation of the line by tilting her hand. But when presented with a tilted slot and asked to insert her hand or to insert a thin object, such as a letter, into the slot, her behavior was in every respect normal – including the acceleration/deceleration and dynamic orienting pattern of her hand as it approached the slot. Her motor system, it seems, knew exactly what orientation the slot was in and could act towards it in a normal fashion.

Another fascinating case of visual processes providing information to the motor control system but not the rest of cognition is shown in cases of so-called blindsight, discussed by (Weiskrantz, 1995). Patients with this disorder are “blind” in the region of a scotoma in the sense that they cannot report “seeing” anything presented in that region. Without “seeing” in that sense, patients never report the presence of objects nor of any other visual properties located in their blind region. Nonetheless, such patients are able to do some remarkable things that show that visual information is being processed from the blind field. In one case, (Weiskrantz, Warrington, Sanders, & Marshall, 1974) the patient's pupillary response to color and light and spatial frequencies showed that information from the blind field was entering the visual system. This patient could also move his eyes roughly towards points of light that he insisted he could not see, and at least in the case of Weiskrantz' patient DB, performed above chance in reporting the color and motion of the spot of light. DB was also able to point to the location of objects in the blind field while maintaining that he could see nothing there but was merely guessing. When asked to point to an object in his real blind spot (where the optic nerve leaves the eye and no visual information is available), however, DB could not do so.

I defer until Section 3.5 the question of whether these facts should lead us to conclude that there are two distinct visual systems, although it is clear from the results sketched above that there are at least two different forms of output from vision and that these are not equally available to the rest of the mind/brain. It appears, however, that they all involve a representation that has depth information and that follows the couplings or constancies or Gogel's perceptual equations (see, Rock, 1997).

3.4.3 Evidence from animal studies

Inasmuch as human brains share many brain-mechanisms and organizational principles with the brains of other animals, it is of interest to ask about perceptual processes in other organisms. Not surprisingly there is a great deal of evidence in animals for a distinction between the vision-for-recognition and vision-for-action functions discussed earlier. The subdivision of the visual output by the functions it is used to perform, goes even further when we consider animals like frogs, where behavior is more stereotyped. In

the case of the frog, (Ingle, 1973; Ingle, Goodale & Mansfield, 1982) found evidence for the separability of visual outputs for feeding, for escape, and for avoidance of barriers. Similar fractionation has also been found in the gerbil, whose visuomotor behavior is not as stereotyped as the that of the frog. (Goodale, 1983; Goodale & Milner, 1982) found that in the gerbil, visual guidance of head turns towards food, escape reactions, and navigation around a barrier, could be dissociated by lesions.

In addition to the dissociation of visual output in terms of the type of motor control functions that they inform, there is another remarkable type of dissociation that was demonstrated by (Cheng, 1986; Gallistel, 1990) which led them to postulate what they refer to as a geometrical module in the rat's visuomotor system. This module seems to only receive visual information relevant to its function of computing orientation relative to the shape of a global environment and cannot take into account identity information. When a rat discovers the location of buried food in a rectangular box and is then disoriented and allowed to relocate the food, it can navigate back to the location of the food by using geometrical cues, where by geometrical cues I mean relative location information, such as "it is near the corner which has a long wall on the left and a short wall on the right". What it cannot do, however, is navigate towards the food by using easily discriminable but non-geometrical visual cues, such as the color or texture or odor of nearby features. But since a rectangle is congruent with itself when rotated 180 degrees, there are actually two locations with the same "geometrical" properties. For this reason, if a rat is placed in a rectangular box where it previously had seen food, it will be indifferent as to which of two geometrically-congruent locations it goes to, even if the correct location is clearly marked by distinctive color, texture or odor cues.

As Gallistel says (Gallistel, 1990, p. 208),

The organ that computes congruence between perceived shape and remembered shape appears to be impenetrable to information about aspects of surfaces other than their relative positions. The congruence computation takes no account of the smells emanating from the surfaces, their reflectance or luminance characteristics, their texture, and so on. It takes no account of the non-geometrical properties of the surfaces, even when the relative positions of the perceptible surfaces do not suffice to establish unambiguously the correct congruence.

This is an example of a function computed by the brain of a rat and other animals, that uses only certain restricted information in the course of carrying out its task (in this case, navigation), even though other information would help to eliminate certain ambiguities, and even though the sensory system of the animal is fully capable of detecting that other information and of using it in different tasks. This is a classic case of the encapsulation or restricted information flow among visual subprocesses that characterizes a modular organization. It is also a case of the visual system being selective in which information it provides to which post-perceptual system.

3.5 Is "vision" one system or many?

We have seen that within the general phenomenon called "vision" there are many subparts. These parts generally work together to produce what I have assumed is the phenomenology of visual perception. This is, in fact, typical of complex system and, as (Simon, 1969) and others have argued, is well motivated both from an evolutionary as well as a functional perspective. But just as I have argued that there is a special distinction between processes specific to vision, as opposed to cognition, so there are those who believe that the visual system should be viewed as comprised of two independent systems. They argue that there are at least two different functions served by vision and that these two functions require rather different processes and different brain systems. The idea that there are two visual systems was perhaps first put forth by (Ungerleider & Mishkin, 1982) who referred to them as the "where" and the "what" systems, with the former being associated with the ventral part of the cortical pathways leading from vision to higher cortical centers and the latter with the dorsal part. From the sorts of evidence discussed above (and developed at great length by (Milner & Goodale, 1995)), it now appears that what really distinguishes these two cortical systems is more accurately described by saying that the dorsal system is concerned with visually guided action while the ventral system is concerned with other functions of vision. Exactly what the right

characterization of the function of the ventral system is remains somewhat less clear, although it appears to include the phenomenal experience we associated with seeing, as well as with recognition of familiar patterns.

Those who prefer to speak of there being two distinct visual systems point to the fact that animals lower on the phylogenetic scale have well developed dorsal systems and have exquisite visual control of their movements. A grasshopper has a very finely developed system for planning and executing accurate jumps, though presumably it does not have an awareness of its percepts nor does it recognize as wide a range of patterns as does a higher mammal. The ventral system, it seems, developed later. Whether this justifies our counting the two functions as constituting different visual systems depends largely on how closely connected the two functions are: We tend to individuate separate “systems” in terms of how constrained the communication is between them. In the case of vision, this is largely an empirical question that remains to be determined with further research. However, there are certain considerations concerning the function of vision that suggest that guiding motor actions and recognizing patterns must be fairly tightly enmeshed.

What is claimed to be special about the computations that go on in the visuo-motor system is: (a) they are quantitative (since the motor system must have a quantitative representation of *where* certain objects are and *how big* they are in order to grasp them), (b) the quantitative measurements are encoded in an egocentric frame of reference (i.e., they are given in a viewer-centered coordinate system, since that is what is needed to reach for objects), (c) the quantitative measurements are made in an absolute system of measurements, as opposed to the sort of relative or normalized system that is appropriate for recognizing patterns irrespective of their size or distance from the viewer, (d) the visual information that is detected and processed may be specific to different motor systems, so that the information that appears to be available to, say, the system responsible for locomotion, may be unavailable to the system responsible for reaching, and (e) in the case of visuo-motor perception, the information is computed very rapidly, with a precision appropriate to the task at hand.

The examples discussed in Sections 2.3.3 and 3.3 show that certain visual information available to the motor system may *not* also be available to other functions, such as the conscious system that reports the content of the percept. But is this a distinction special to the visual system? One of the important discoveries of modern cognitive science is arguably the finding that the distinction between the information of which one consciously aware and that of which one is not consciously aware is of marginal relevance to inferring the nature of the information-processing operations that occur. The notion of “tacit knowledge” plays a role in cognitive science analogous to the notion of “invisible particles” in physics: Both are indirectly inferred from available evidence, as opposed to being observed directly (Fodor, 1968; Pylyshyn, 1981). The tacit perceptual knowledge involved in both of the hypothesized kinds of visual processes may be the same – i.e., they may both be functional and demonstrable by indirect experimental evidence. The more important question is whether there are objectively measurable functions other than conscious reporting that are served by the ventral system and whether these functions can be shown to depend on different information than those controlling motor actions.

I have been discussing some properties of what I called the “architecture of the visual system”. This refers to certain “fixed” properties of visual processes. The notion of architecture is central to understanding mind and I have devoted considerable attention to what it means, why we must study it, and what we know about it. Some of this discussion will appear again in chapter 5 where it becomes an essential part of understanding claims about the use of the visual system in mental imagery. What I discussed so far in this chapter are certain large-scale structural properties of the visual system. In the last chapter I discussed evidence showing that vision (or early vision) forms a distinct module of the mind – that the architectural structure of the mind is such that vision is a separate component loosely tied to the faculty of reasoning. In this chapter I showed that vision itself exhibits an architectural structure – that functionally it consists of component parts with restricted lines of communication among them. But there is another important set of questions that can be addressed regarding the architecture of vision besides the question of how it divides into component parts. If architecture represents a set of relatively fixed properties, then these properties must explain how it manages to be so smart. Many investigators have remarked on the

“intelligence” of vision (Richard Gregory calls it “the intelligent eye,” Irvin Rock speaks of “visual problem solving” and Don Hoffman uses the term “visual intelligence”, see Gregory, 1970; Hoffman, 1998; Rock, 1983). Given visual cues that are inherently ambiguous, vision seems to come up with an analysis or a “solution” that is very often veridical and in doing so appears to take into account factors that imply a faculty of intelligence of some sort. If its architecture is fixed and not malleable by what the organism knows, then how does it manage so often to produce an intelligent analysis of its input? This is the question that many investigators have addressed, but few have done so in the kind of detail that people have when attempting to develop computer systems that can emulate human vision. The computational vision field has inspired many vision scientists to look for properties of vision that are fixed (in the sense of not changing with the changes in the observer’s system of beliefs and knowledge) and yet explain how vision comes to the analysis it does, at least in the human vision case. If we cannot explain the apparent intelligence of vision in terms of its architecture, then we may be forced to conclude that it is privy to the intelligence of the whole observer. Because of this it behooves us to look at some examples of such “intelligent” visual analyses and consider what this tells us about the architecture of vision.

4. FOCAL ATTENTION: HOW COGNITION INFLUENCES VISION

The last chapters defended the view that a certain part of vision, referred to as *early* vision, is encapsulated so that its operation is unaffected by cognitive processes, such as inference from general knowledge. But clearly early vision does not function passively for the organism but rather it exists in the service of cognition. Even though cognition may not affect how early vision operates, it does exert some control over *what it operates on* and it can also make judgments about what in fact might have caused certain perceptual experiences. Chapter 2 suggested that focal attention provides one of the two primary means by which the cognitive system can influence vision (post-perceptual recognition and decision processes is the other), and that it does so by selectively directing the visual process to certain aspects of the perceptual world. Clearly it is important to constrain what can serve as the object of attentional focus. If *anything* could count as a possible focus of attention, then the idea of attention would be devoid of explanatory value since we could always explain why two people (or the same person on different occasions) appear to see things differently by claiming that they were “attending” to different aspects of the world, which comes to pretty much the same claim as that vision is cognitively penetrable, contrary to the assumption I defended concerning early vision. The following sections will elaborate on the role that a suitably constrained notion of attention can play in allowing cognition to have a certain specific sort of effect on visual perception. Then the next chapter will develop these ideas further and show that certain mechanisms involved in visual attention also serve a quite different and in many ways a more fundamental role, that of linking parts of the percept to the *things in the world* to which they refer.

4.1 Focal attention in visual perception

One of the ways in which the cognitive system can influence perception is by choosing *where* or *at what* to direct the visual process. We obviously affect what we see when we choose *where to look*. Indeed changing our direction of gaze by moving our eyes is one of the principle ways in which we selectively sample the visual world. But it turns out that there is much more to the notion of selectively attending. For example, it is known that we can also direct our attention without moving our eyes (using what is referred to as “covert” attentional allocation – see section 4.3). Moreover attention can also be directed to certain properties rather than particular places in a scene. Indeed, there is reason to believe that at least some forms of attention can only be directed to certain kinds of visible objects and not to unoccupied places in a visual scene, and that it can be directed to several distinct objects. In what follows I will examine some of this evidence and its implications. Whatever the detailed properties of attention, and whatever kinds of mechanisms it presupposes, we will see that what is called *selective* or *focal* attention represents the primary locus of cognitive intervention between our perception and the physical world we perceive.

There are a number of far reaching implications of this way of understanding attention. It suggests that focal attention determines what we “notice” and therefore ultimately what we see. We take it for granted that there is always more that *could have been noticed* than actually was noticed. And that, in turn, is an informal expression of the view that visual processing is limited in some way and therefore has to make choices about how to allocate its limited resources. This is indeed the basic idea behind the last 50 years of study of focal attention (but see, Kahneman & Treisman, 1984, for an early recognition that this is a limited perspective). In addition to determining which aspects of the world will get processed, the allocation of focal attention also has implications for the way in which visual perception carves up the world into distinct things – how the world is “parsed”. As suggested in chapter 2, because of its key role as a gatekeeper between vision and the world, the allocation of attention is also one of the main loci of perceptual learning. Moreover, as we will see in chapter 5, certain mechanisms of early vision that are closely related to attention may also determine the way our percepts and our concepts are connected to the world. And because it provides the principle interface between cognition and vision, focal attention also plays an important role in mental imagery, since the generation and processing of visual mental images appears to share properties of

both vision and cognition. This will be the topic of Chapter 6. First some background on visual focal attention.

4.2 Focal attention as selective filtering

Attention is an ancient and ubiquitous concept. The term has been used to refer to a wide range of phenomena, from simply having an interest and motivation towards some task (as in “paying attention”), to the filtering function that was widely studied in the 1950s, due in no small measure to the seminal work by Colin Cherry (Cherry, 1957) and Donald Broadbent (Broadbent, 1958). These different senses of attention share, at least by implication, the assumption that the cognitive system cannot carry out an unlimited number of tasks at the same time, and therefore must choose or select the task (or tasks) to which it will direct its limited resources. Beyond this general idea, the notion of attention has been treated in very different ways by different researchers and by different schools of psychology. Regardless of the approach and the emphasis placed on different aspects of attention, the centrality of its role in visual perception has always been recognized. In the early 20th century the main concern was with the question of how attention increases the awareness or clarity of attended aspects of the perceptual world. Later the emphasis turned to the selectivity of perception and on the properties that enabled certain information to be passed while others (the unattended aspects of the world) were filtered out. Broadbent’s “filter theory” played a major role in these discussions (which are summarized in Broadbent, 1958; as well as in Norman, 1969).

The reason for the importance of filtering arises from the assumption of limited processing resources. One of the most fundamental and widely accepted assumptions about human information processing is that, however it works in detail, its resources are limited. For example, there are limits on its working memory capacity, on the speed and reliability with which it can carry out operations, on the number of operations it can carry out at one time, and so on. The assumption of limited processing resources leads immediately to several important questions:

1. *If information-processing is limited, along what dimensions is it limited? How does one measure its limits?*

This is a deeper and more fundamental problem than might appear at first glance. In the 1950’s the dimension of limitation was sometimes referred to as the “range of cues utilized” (Easterbrook, 1959). But under the widespread influence of information theory in psychology, it was common to look for limitations in terms of bandwidth, or entropy measures (i.e., in terms of number of bits per second). In a classical paper, George Miller (Miller, 1956) argued, however, that the limit of short-term memory (now often called “working memory”) was not in the amount of information it could hold, as measured in information-theoretic terms (such as in the number of “bits” of information), but in the number of discrete units of encoding or “chunks”. This was a very important idea and had an enormous influence on the field, despite the fact that what constitutes a “chunk” was never fully spelled out and this lack of specificity has always remained a weak point in the theory. Another proposal (Newell, 1972), similar to the working-memory limit idea but differing in details, is that there are limits on how many arguments could be bound in evaluating cognitive functions or subroutines. A variant of this, proposed later by (Newell, 1980a), is that rather than a fixed limit on the number of arguments allowed, there are certain costs, and hence potential speed-accuracy tradeoffs, associated with increasing the number of bound variables.

While the notion of resource limits is well entrenched, there is no general agreement on the nature of the information processing “bottleneck” in visual information processing. The theoretical position that will be describe in Chapter 5 provides one view of where the bottleneck resides: It attributes it to a limitation on the number of arguments in a perceptual function or predicate that can be bound to extrinsic objects.

2. *Limited capacity information processing implies that a decision has to be made about where (or to what elements, properties, modalities, or more generally “channels”) to allocate the limited capacity. How and on what basis is this decision made?*

The first part of the question asks which properties (or perhaps what entities) can be the target of selective attention. This question cannot be given a simple univocal answer. In Chapter 2 I discussed some evidence that attention may be directed to certain properties or range of properties of a stimulus. For example, it has been shown that people can focus their attention on various frequency bands in both the auditory domain (Dai, Scharf & Buss, 1991) and in the visual spatial domain (Julesz & Papatomas, 1984; Shulman & Wilson, 1987), and also under certain conditions, on such features as color (Friedman-Hill & Wolfe, 1995; Green & Anderson, 1956), local shape (Egeth, 1984 #841], motion (McLeod, Driver, Dienes, & Crisp, 1991) or stereo disparity (Nakayama & Silverman, 1986). But there must be some principled restrictions on what can serve as the basis for selective attention, otherwise the notion would be of no use as an explanatory construct: We could (vacuously) explain why some people (e.g., Bernard Berenson) are experts in identifying paintings by Leonardo DaVinci by saying that they had tuned their visual system to attend to the particular visual properties that are characteristic of DaVinci paintings. This issue is closely related to the reason why such properties as those that James Gibson (Gibson, 1979) called “affordances” (which includes properties such as being edible or graspable or sit-on-able) cannot be the subject of attending or of direct “information pickup”, at least not in any useful sense of attending, meaning a selection that can be accomplished prior to perceptual interpretation. In (Fodor & Pylyshyn, 1981) we noted that if properties such as being a recognizable familiar object (such as a shoe), or being a particular affordance could be the basis of primitive selection or, as Gibson put it, could be *directly picked up*, then there could not be misperception of such properties – which is patently false since it is easy enough to make something *look like* it had a certain affordance even though it doesn’t (it could, for example, be a hologram). For this and other reasons we concluded that only a highly constrained set of properties can be selected for by early vision, or can be directly “picked up.” Roughly these are what I have elsewhere referred to as “transducible” properties (Pylyshyn, 1984a, chapter 9). These are the properties whose detection does not require accessing memory and drawing inferences. Roughly speaking, visually transducible properties are either optical properties or are defined in terms of such properties without reference to the perceiver’s knowledge or beliefs; they are functions of the architecture of the visual system, in the sense discussed earlier in this book. Detection of such properties is sometimes referred to as being *data-driven*. These properties clearly exclude *being edible* or *being a genuine Da Vinci painting* since detecting these depends on what you know about the world, including what you learned from books. Properties that cannot be visually transduced in this sense cannot serve as a basis for filtering.

The view that attention is a selective filter whose function is to keep perceptual resources from being overloaded raises another serious question. If the role of attention is to filter out certain visual information in order to prevent overloading, then the information filtered out in this way cannot have any influence on perception. If it did then attention would not have accomplished its goal inasmuch as the visual system would have had to process all the information anyway. A great deal of research has been done on the question of whether unattended (or filtered-out) information is completely eliminated from the perceptual system. Some of the earliest investigations were carried out on the auditory system by (Broadbent, 1958) and by (Treisman, 1969). They generally found that the more a property could be characterized in terms of basic physical dimensions, the more readily it could be filtered out. For example it is easier to filter out a speech stream defined by pitch or by which ear it is presented to, than by which language it is in. And which language the information is in is, in turn, an easier basis for filtering than is the topic it is on. Distinguishable properties of a class of signals are often referred to as “channels” and the simpler the physical specification of the channels, the better the filtering. Despite the large amount of evidence accumulated that showed the operation of channel filters, the research also showed that even when certain information appears to have been filtered out (e.g., observers are unable to report it), it nonetheless still has measurable consequences. (Norman, 1969; Pashler, 1998, Chapter 2) describe a large number of experiments illustrating the “leakiness” of such filters. For example, a common paradigm involves presenting different information to the two ears (the so-called “dichotic presentation” method). These studies showed that information that was ostensibly filtered out (and could not be reported by observers) could nonetheless be shown to have consequences. Information in the “rejected” channel could even affect the interpretation of signals in the attended channel. For example, if the attended channel contained a lexically ambiguous word (e.g., the word “bank” which can mean either an institution or the land bordering

on a river), the rejected message affected which reading was more frequently given to it (e.g., Lackner & Garrett, 1972, showed that if the rejected message was on a financial topic the institutional sense of “bank” was reported more often in the attended channel). Also the extent to which the presence of material in the rejected channel disrupted the material in the attended channel depends on whether the observer could understand the message in the rejected channel (e.g., if it was in a different language, the amount of disruption depends on whether the observer understands that language, and so on, see Treisman, 1964). This presents a puzzle for a pure filter theory since the criterion of being able to understand the language presupposes that the rejected information was available after all. The next section provides other examples from vision showing that apparently ignored information can have important and long-lasting effects.

Despite a number of different ways of attempting to reconcile these findings within a pure filter theory of attention, the results have generally been inconclusive.²⁸ It seems as though for each putative channel or filtering property P, there are experiments showing that (a) items in the rejected channel (or items which do not have property P) are in fact being processed, and (b) the determination as to whether an item has property P is often made after the stage at which filtering needs to have occurred in order to ease the processing load. Also it seems as though attention may have sharper and more clearly delineated consequences on what we are consciously aware of than it has on what is actually processed by the brain. This related to the observation I made in Chapter 1: The phenomenology of vision is an unreliable basis for concluding whether some visual information has been processed. The fact that an observer may be unaware of certain “unattended” information does not mean that such information has not been processed and has not had an effect on the rest of the cognitive (or motor) system. And, as we have also seen, the converse is also true: What we subjectively experience in vision may provide a misleading basis for concluding what information has been assimilated or encoded.

4.3 Allocation of visual attention

Beginning around 1980, the study of visual attention tended to emphasize the role of spatial location in determining how visual information is processed. The major impetus for this tradition was the discovery that in order to shift attention in a particular direction it was not necessary to move one’s gaze in that direction: attention could be moved “covertly” without eye movements. Many investigators (perhaps beginning with Shulman, Remington & McLean, 1979) have shown that attention appears to move continuously through space. Shulman et al. instructed subjects to move their attention in a given direction and found that the detection of a faint stimulus was enhanced at various intermediate places along the direction of attention movement. Subsequently (Posner, 1980) undertook a systematic analysis of what he referred to as the orienting of attention. He (and many other investigators, Tsal, 1983) showed that if attention was automatically attracted towards a point in the periphery of the visual field then stimuli along the path were more easily discriminated at various intermediate times. For example, Figure 1 shows one such experiment, using what is called a “cue-validity” procedure. A brightening of a spot either to the right or to the left of fixation provides a cue as to where a target will be on 80% of the trials. When the target does appear at the cued location, the time it takes to detect it is faster than when it appears in the invalid cue location. Moreover, the time by which the cue signal is delayed determines how effective the cue will be. The time delay for maximum effectiveness (shortest relative reaction time) provides an indication of how long it took for attention to arrive at that location. From measurements such as these, various researchers estimated the rate at which attention moves across a scene in such automatic, gaze-independent (or “covert”) situations. These estimates cover a wide range; 4 msec/degree (Posner, Nissen & Ogden, 1978), 8.5 msec/degree (Tsal, 1983), 19 msec/degree (Shulman et al., 1979), 24-26 msec/degree (Jolicoeur, 1983). But the idea that attention does move through empty space was widely accepted.

²⁸ For example, it does not help to assume that the signal in the rejected channel is merely attenuated, rather than completely filtered out. That just makes it the more surprising that the content of the attenuated signal has an effect on analysis of the attended channel.

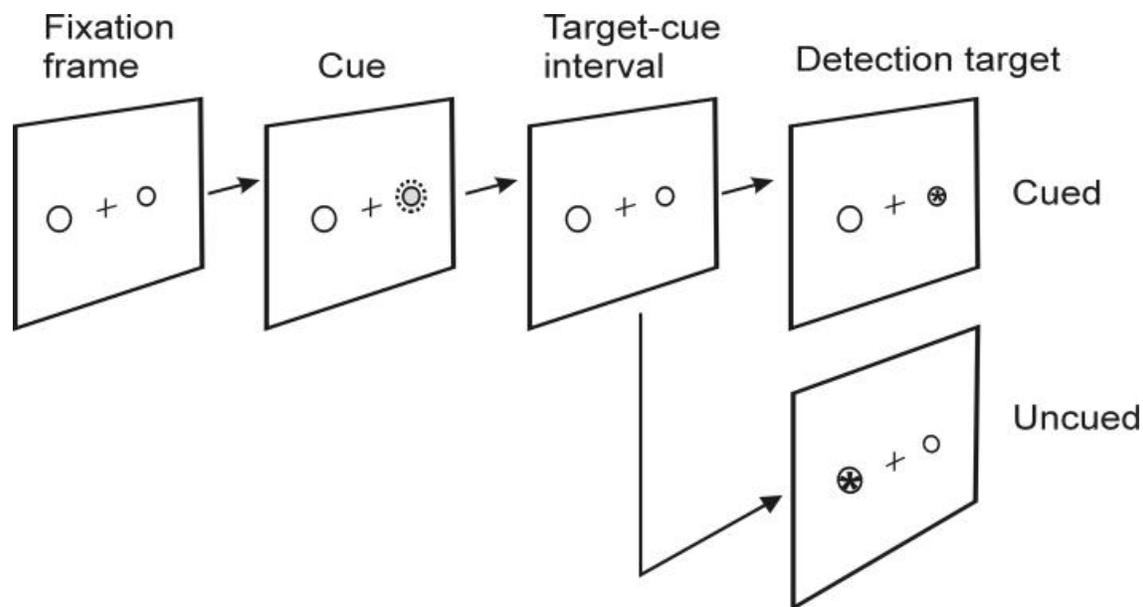


Figure 4-1. An example of an experiment using a cue-validity paradigm for showing that the locus of attention travels without eye movements and for providing an estimate of its speed (based on Posner, 1980).

The study of such covert movements of attention occupied a great deal of research effort during the 1980s. Various mechanisms were proposed to account for this apparent movement of attention, including the widely-cited “spotlight” metaphor (Posner, 1980), as well as mechanisms not involving a discrete moving locus, such as proposals involving increasing and decreasing activation at two loci that results in a spreading pattern which can appear as a moving maximum of attention (Hikosaka, Miyauchi & Shimojo, 1993; McCormick & Klein, 1990; Schmidt, Fisher & Pylyshyn, 1998; Sperling & Weichselgarter, 1995). For example (Sperling & Weichselgarter, 1995) defend an “episodic” theory that assumes that attention decreases at the point of origin and both increases and spreads at the new focal point. They showed that from this assumption one would predict that at various times after the occurrence of the detection target (as in the rightmost panel of Figure 4-1) the sensitivity at intermediate locations would follow the pattern found by Posner. Regardless of the underlying mechanism, a large number of experiments showed that the locus of attention appears to move rapidly and from place to place under either automatic external (“exogenous”) control or under voluntary cognitive (“endogenous”) control. Exogenous control can be accomplished by presenting certain cues that reliably capture attention – the most robust of which are the sudden-onset of new visual elements – whereas endogenous control is typically illustrated by providing cues that inform subjects in which direction to move their attention (e.g., using an arrow that appears at fixation). Although both types of attention shifting cues show attentional-enhancement at the cued location, there are differences in both the type of enhancement and its time-course for these two sorts of attentional control. For example a number of studies (e.g., Henderson, 1991; Van der Heijden, Schreuder & Wolters, 1985) have shown that accuracy of discrimination is improved only by exogenous cues. Moreover, it has been shown (Mueller & Findlay, 1988; Mueller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Shepherd & Mueller, 1989) that facilitation of response to exogenous cues appears earlier and is stronger than the facilitation to endogenous cues. Attentional facilitation in response to exogenous cues is maximal approximately 100-150 ms and fades within 300 ms after cue onset. Moreover, when such cues actually identify target locations to which subjects respond, the early peak facilitation produced by exogenous (but not endogenous) cues is followed after about 500 ms by inhibition (so-called “inhibition-of-return”). Despite the difference between exogenously and endogenously triggered attention movement, and despite different theoretical interpretations of the various results it is generally accepted that attention *can* be moved without eye movements. Indeed it is widely held (Kowler, Anderson, Doshier, & Blaser, 1995) that a covert

attentional movement *precedes* the overt movement of the eyes to certain locations in a scene, though such a covert movement may not be essential for an eye movement to take place.

In addition to the covert control of the locus of a spatially localized attention focus, it has generally also been held that people can control the extent or breadth of the focus of attention. For example, (Eriksen & St. James, 1986) have argued that observers can widen the scope of their focus at the cost of decreasing the level of attention allocated to certain regions. This so-called “zoom lens” view of attention has had detractors as well as supporters. In addition to the evidence that attention can be moved covertly and can be expanded or zoomed, there is also evidence that it can spread to certain shapes (such as bars or even letter-shaped templates) providing that some visible anchors for these shapes are available. In the latter case such shaped attention profiles can be used to facilitate the detection of brief stimuli on those forms. For example, (Farah, 1989) showed subjects the matrix on the left panel of Figure 4-2, where 19 of the cells are colored a faint gray, and asked them to attend to either the cells corresponding to the H subfigure region or the T subfigure region (shown in the other two panels). When they did this their sensitivity to detecting a dim flash of light within the attended region was enhanced, suggesting that they could spread their attention at will over a region defined by specific visible squares. Subsequent experiments (see section 4.5.2) also showed that cuing of part of a shape would spread to enhance the sensitivity to the whole shape.

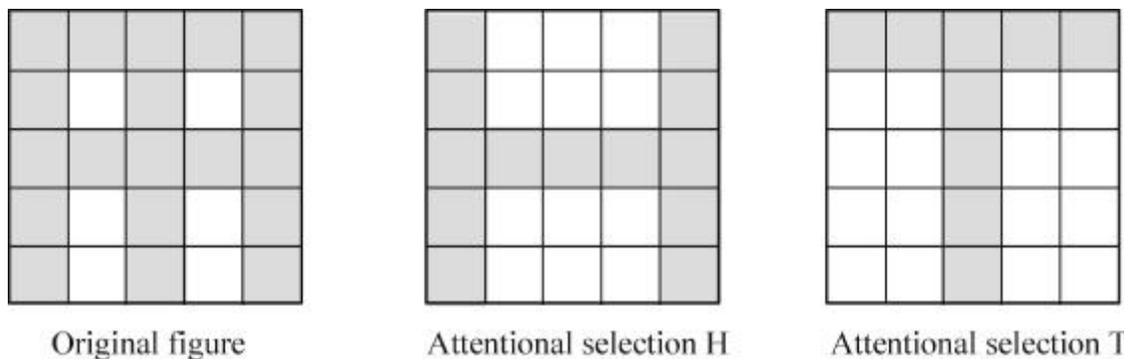


Figure 4-2: Studies showing that people can allocate attention to certain well-defined regions (after Farah, 1988).

In a related experiment, (Hayes, 1973) showed that subjects are better at recognizing a certain pattern if they are first shown the exact shape, size and location of pattern that they are to expect. Such findings have often been taken as evidence that subjects can project an image onto a visual display. However, these findings can easily be explained if one assumes that what subjects are doing is allocating attention to a regions defined by certain simple visible objects (including simple texture elements) on the display screen, just as they did in the (Farah, 1989) study described above. Such an explanation also makes sense in view of other findings (e.g. the studies by Burkell & Pylyshyn, to be discussed in Chapter 5) which show that a phenomenon generally associated with focal attention (namely priority of access) can be split across several disparate objects in a display. Thus it appears that some form (or stage) of attention can be focused on larger areas and shapes and can be split across distinct elements. Later I will suggest that this form of attention is actually allocated to objects rather than to regions and that the multiple-object-based phenomenon is more primitive than what we generally understand by the term attention.

(Rock & Gutman, 1981) showed that the patterns people attend may be distributed over a relatively large area and can be kept separate from distinct overlapping regions. They showed subjects figures such as the ones in Figure 4-3. Observers were asked to make aesthetic judgments about the shapes that were in a particular color (e.g. the green figures) while ignoring the other shapes in the display. After viewing about 10 such displays the subjects were given a surprise recognition test. They were able to recall the items they had attended with the same level of performance as if they had been presented alone, but their recognition of the rejected items was nearly at chance. (Brawn & Snowden, 2000) used a priming paradigm (see section 4.5.2) with overlapping figures (they used a figure like Figure 4-19, except with circles added at each

vertex) and showed that when observers saw the figure as two distinct shapes, then attention spread over the single primed figure and not the unprimed one.



Figure 4-3: Figures similar to those used by (Rock & Gutman, 1981) to show that attention can be allocated to whole figures even when the figures are intertwined among other figures.

The Rock & Gutman study answers the question of whether an entire distributed shape can be attended even when it is entwined with another (often more familiar) shape. The answer is that at least for the purpose of entering into memory, entire shapes can be encoded to the exclusion of equally prominent overlapping shapes. But the study does not answer the question of whether the unattended shape is processed in any way. This question has received opposite answers in a number of studies. One important set of studies (reviewed in Mack & Rock, 1998a) found what has become known as *Inattentional Blindness* (IB). These studies showed that shapes that are not attended receive almost no processing and are unavailable to conscious awareness and recall. The demonstrations are quite dramatic. For example (Mack & Rock, 1998b) showed that small squares presented unexpectedly right at fixation are not noticed if the observer is engaged in another more peripheral visual task and is not expecting them. Indeed the evidence seems to suggest that when no new information is expected at particular marked locations, observers actually *inhibit* attention and encoding of information into memory, leaving an apparent blindness at those marked locations. If the location where the surprise event is to occur is not marked by the presence of a visible feature, however, no inhibition of such an unoccupied location is observed (Mack & Rock, 1998a, 1998b). This finding is consistent with the view, to be developed below, that both attention and inattentional blindness is object-based since it is not regions in space that are inhibited, but entire individual objects. The inhibition of non-selected shapes has also been demonstrated in search experiments by (Watson & Humphreys, 1997), so there appears to be some consensus on the role of object-based inhibition as well as object-based attention as a mechanism for shutting out information about irrelevant or unwanted objects.

Other studies, however, appear to show that at least *actively* ignoring objects has a strong long-term effect. A number of studies (see the review in Fox, 1995) asked subjects to identify or otherwise attend to certain figures – e.g., those in a given color – while ignoring other overlapping figures. At a later stage in the experiment one or more of the stimuli initially ignored (unattended) appeared as stimuli about which some judgment was required. When the figure had appeared earlier as one that had to be ignored, it took longer to identify (or otherwise respond to). This phenomenon, called “negative priming” has been the subject of a great deal of research and a number of remarkable findings have been reported. For example (DeSchepper & Treisman, 1996; Treisman & DeSchepper, 1995) used random shapes similar to the Rock & Gutman shapes of Figure 4-3 in a discrimination task. Two figures were presented. The one on the left contained two overlapped figures as on the left of Figure 4-3. On the right was a single figure. Subjects had to judge whether one of the overlapped figures on the left, say the red one, was identical to the single figure on the right. The time it took to make this judgment was very sensitive to whether the test figure on the right had earlier appeared as the nonattended figure on the left. If it had, the reaction time was significantly longer, even if the figures were totally novel. It seems that a representation of an individual shape is created even

for figures that are ignored. (DeSchepper & Treisman, 1996) report that the negative priming effect is robust enough to last through over 200 intervening stimuli and even to persist for as long as a month. It is apparent that unattended shapes are encoded somehow and leave a lasting trace, even though, according to both the Rock & Gutman and the DeSchepper & Treisman studies, there is essentially zero explicit recall of them. Both the incidental recall study of Rock & Gutman and the negative priming effect suggest that attention is paid to entire figures, even when the figure is extended and when it is intermingled with other figures that are ignored – and indeed, even when they appear to have been ignored as judged by explicit recall measures. (Additional related findings on the tendency of attended objects to refrain from attracting attention immediately after they have been attended – so called Inhibition of Return – will be discussed below in section 4.5.3). The negative priming results also suggest that the naïve notion of attention as a focal beam that is necessary for memory encoding may be too simplistic. These findings fit well with a growing body of evidence suggesting that something like attention may be allocated to individual objects very early in the visual stream.

Although I have been concentrating on attentional selection from visual displays, the notion of object-based attention is not confined to static visual objects. Some time ago (Neisser & Becklen, 1975) showed that people can sometimes selectively follow one of several complex sequences of events – for example they can selectively attend to one of two games superimposed on a video. There is also evidence that objecthood is a much more general notion and that it applies to not only to spatially defined clusters, but also to clusters defined by other properties, as for example in various forms of “streaming” (to be discussed in greater detail later, see Figure 4-14) that occurs not only in vision but also in audition, where auditory streaming (in which a series of superimposed notes may appear not only as single sequence of chords but also under certain conditions as two or more distinct overlapping melodies) are well studied phenomena (Bregman, 1990; Kubovy & Van Valkenburg, 2001).

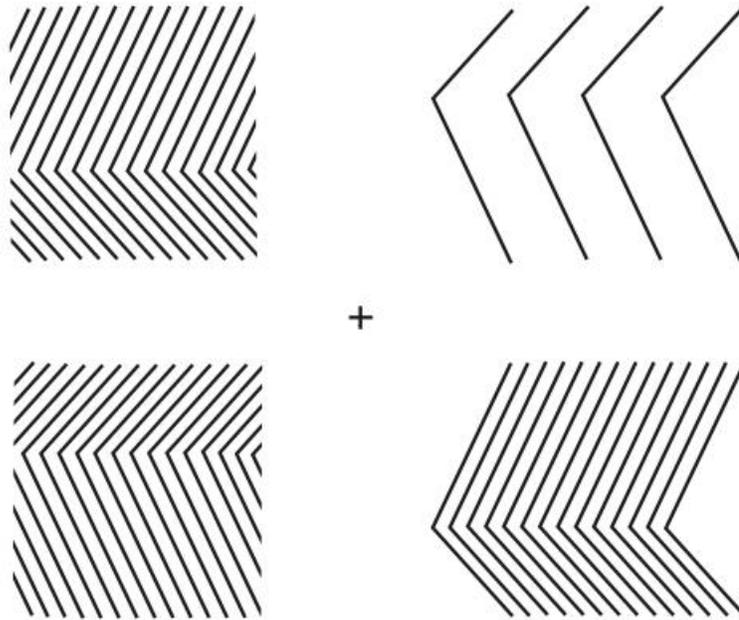
4.4 Individuation: A precursor to attentional allocation?

4.4.1 Individuation is different from discrimination

The surprising negative priming result discussed above raises the question of whether what we intuitively refer to as “attention” is really a single process, or whether there are different stages in the process responsible for the phenomena we class as “attention”. In this section, as well as in chapter 5, I suggest that there are a number of reasons to believe that *individuation* of what, for now, I will call *visual objects*²⁹ is a primitive operation and is distinct from discrimination and recognition and, indeed, from what we generally call “attention”. Individuation appears to have its own psychophysical discriminability function. (He, Cavanagh & Intriligator, 1997) showed that even at separations where objects can be visually resolved they may nonetheless fail to be *individuated*, preventing the individual objects from being picked out from among the others. Without such individuation one could not count the objects or carry out a sequence of commands that require moving attention from one to another. Given a 2D array of points lying closer than their threshold of individuation, one could not successfully follow such instructions as: “move up one, right one, right one, down one, ...” and so on. Such instructions were used by (Intriligator, 1997) to measure what he called “attentional resolution” and what I refer to as “individuation”. Figure 4-4 illustrates another difference between individuating and recognizing. It shows that you may be able to recognize the

²⁹ In the context of attention studies such as those to which I alluded above, the elements in the visual field are typically referred to in the psychological literature as “objects” where the exact referent of this term is deliberately left ambiguous. In particular it is left open whether what is being referred to are enduring physical objects, proximal visual patterns or some other spatially local properties. The only property that appears to be entailed by the term in this context is that it endures over changes in location, so that when we call something an object we imply that it retains its individuality (or, as it is sometimes called, its “numerical identity”) as it moves about continuously or changes its properties over a wide range of alternatives. In every case considered here, “object” is understood in terms of whether something is perceived as an individual. Is it possible to have an objective definition of “visual object”? We will return to this issue later, but our conclusion will be that while something like “primitive visual object” can be defined by reference to certain theoretical mechanisms, it will remain a viewer-dependent notion (or, as philosophers would say, the concept is mind-dependent). Moreover, in our usage we confine ourselves to *visual* objects, not to real physical objects, although as we will see, the two are closely linked.

shape of objects and distinguish between a group of objects and a single (larger) object, and yet not be able to focus attention on an individual object within the group (in order to, say, pick out the third object from the left). Studies reported in (He et al., 1997) show that the process of individuating objects is separate and distinct from that of recognizing or encoding the properties of the objects. Perhaps, then, one must individuate objects even before one can attend to them.



*Figure 4-4. At a certain distance if you fixate on the cross you can easily tell which groups consist of similar-shaped lines, although you can only **individuate** lines in the bottom right group. For example, you cannot count the lines or pick out the third line from the left, etc., in the other three groups.*

Studies of rapid enumeration of small numbers of objects, known as subitizing, have also thrown some light on the distinction between individuation and other stages in visual processing. The phenomenon of subitizing has been studied for a long time and it has generally been recognized that small and large numbers appear to be enumerated differently: sets of 4 or fewer objects are enumerated more rapidly and more accurately than larger sets. The reason for this difference, however, has remained a puzzle. (Trick & Pylyshyn, 1994b) showed that items arranged so they could not be preattentively individuated couldn't be subitized, even when there are only a few of them. For example items identified in terms of operations that must be performed serially or that require focal attention in order to be selectively picked out or individuated – such as “dots lying on the same curve” or elements specified in terms only of conjunctions of features (e.g. all elements that are both red and slanted to the left) cannot be subitized – i.e., the rate of enumeration does not change when the number of objects exceeds around 4, as shown by the fact that the graph or reaction time as a function of number of items does not have a “knee”.³⁰ An example of elements arranged so they can or cannot be individuated preattentively is shown in Figure 4-5. When the squares are arranged concentrically (as on the left) they cannot be subitized whereas the same squares arranged side by side can easily be subitized. Trick & Pylyshyn provided an explanation for this phenomenon that appeals to a theory that will be discussed at length in the Chapter 5. However a critical aspects of the explanation is the

³⁰ This was determined by analyzing linear and quadratic components of the pattern of increasing reaction time with increasing number of objects n to be enumerated. Items that are subitized undergo a change at some value of n when the quadratic component of the trend becomes significant. This is taken to be the subitizing point (see, Trick & Pylyshyn, 1994b). Sets that are not subitized either fail to attain a significant quadratic trend or, more likely, fail to have a significant linear effect even at a small value of n .

assumption that individuation is a distinct (and automatic) stage in early vision and that when the conditions for automatic individuation are not met, then a number of other phenomena that depend on it, such as subitizing, are not observed. Notice that the individual squares are clearly visible and distinguishable in both versions of Figure 4-5, yet in the figure on the left they are not automatically individuated and therefore not easily counted or subitized.

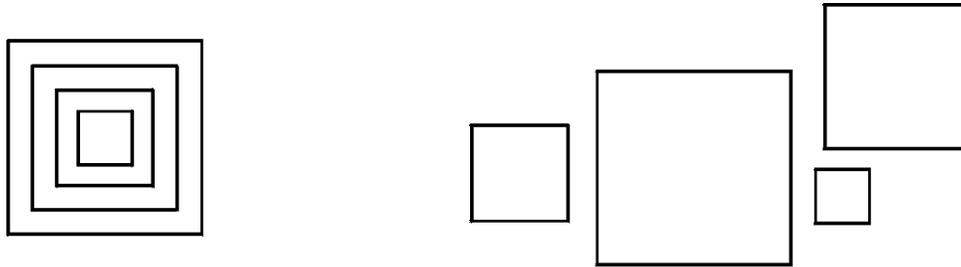


Figure 4-5. Squares arranged so they cannot be preattentively individuated (on the left) cannot be subitized, whereas the ones on the right are easily subitized (based on Trick & Pylyshyn, 1994b).

4.4.2 Individuating an object is distinct from encoding its location or visual properties

It appears that under certain conditions there is dissociation between the detection of certain properties and the perception of where those properties are located. For example, Anne Treisman and her colleagues showed that when focal attention was directed at a particular item in a display, certain properties of other (unattended) items in the display could still be reported, but in that case combinations of those properties were frequently assigned to the wrong items in what are called “conjunction illusions”. For example, (Treisman & Gelade, 1980; and Treisman & Schmidt, 1982) found that if attention was distracted by a subsidiary visual task (such as reading digits aloud) subjects frequently reported seeing the correct shape and color of items in a display like the one shown in Figure 4-6 below, but with false combinations or *conjunctions* of color and shape (e.g., they reported that the display contained a red X and a green O when in fact it had contained a green X and a red O). Moreover, when subjects were required to search for a particular target in a display they were faster at scanning the display when they were looking for disjunctions of properties (e.g., find either an X or a red figure in a field that consists of both red and green Xs and Os) than when they were looking for conjunctions of properties (e.g. find the single red X in a field of both red and green X’s and Os). A large number of studies established a variety of further properties of such rapid search and led to what is known as *Feature Integration Theory*, which claims that a major role of focal attention is to allow distinct features to be bound to the same item, solving what is called the binding problem for properties. This *attention-as-glue* hypothesis helps to explain a variety of findings and has played an important role in the development of current views of attention.

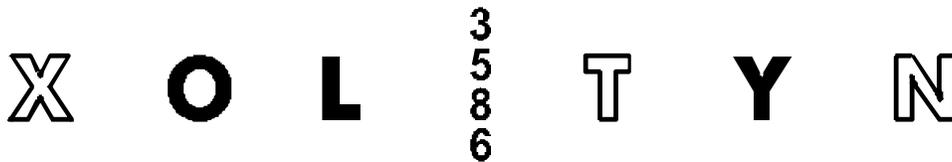


Figure 4-6: Displays leading to conjunction illusions. In the experiments, subjects read the numbers at the center of the display then, after the display is extinguished, report the letters and their colors. Try reading the numbers, then close your eyes and report letters and colors (the solid black letters are meant to indicate red letters while open shapes indicate green letters).

Illusory conjunctions appear with a large variety of properties including shape features, so that a display with \-shaped (left oblique) lines, L-shaped figures and S-shaped figures led to the misperception of triangles and dollar signs. It seems as though attention is required in order to bind properties together. Such findings

have typically been interpreted as suggesting that when features are detected, their location remains uncertain until the feature is attended. There is considerable evidence that some properties of a visual object may be detected while its location is either misidentified or unknown. Thus you might see that a display contains the letter X but fail to correctly detect *where* it was located, or “see” it to be at the wrong location (Chastain, 1995). There have been a number of discussions in the literature of the role played by the *location* (of objects or features) in the initial encoding of a visual scene. The idea that the location of features is subject to uncertainty serves as an assumption of several models that have been developed to explain certain aspects of the conjunction illusion, mentioned in the last paragraph. For example, contrary to the original claim made by (Treisman & Schmidt, 1982), it now appears that the frequency of conjunction illusions may depend on the distance between objects whose properties are erroneously conjoined, as well as on the similarities among the particular properties themselves. (Ashby, Prinzmetal, Ivry, & Maddox, 1996) have argued that it is the inherent uncertainties in both the features and their location, combined with various response selection strategies, that explains both the distance and the similarity effect in the occurrence of conjunction illusions. Ashby et al. present a detailed mathematical model that is able to sort out various types of response biases and noise sources in detection experiments. This model, like all other theoretical discussions of the conjunction illusion, does not distinguish between *individuation* of a visual object (or recognizing something in the visual field *as* a particular individual object) and encoding its location. Thus, for example, the only sources of uncertainty that are considered are the location and the type (e.g., shape or color) of the features involved in the conjunction error. Yet even after one has encoded such properties as location, shape and color, there is still the question of whether one has assigned these properties to a *particular individual object*, and if so, which one. This distinction is particularly cogent when all dimensions – including location – are changing. The question then is whether we make conjunction errors by misassigning properties to an individual object as it moves about, or whether we assign the detected properties to the location occupied by that property at some particular time, but do so with a certain degree of error. Other alternatives are also possible. For example, it might be that there is no uncertainty about assigning properties to objects, but under certain conditions there is uncertainty in deciding when two objects which have been assigned properties, are actually the *same* object. I will return to these possibilities later when I discuss the assumptions underlying our account of the incremental computation of percepts in Chapter 5. There I make the assumption that when an instance of a property is detected, it is detected *as the property of an individual object*. Distinguishing *which* object it is is typically done by a preattentive and preconceptual mechanism (or so I will argue in Chapter 5), although recognizing the object’s identity may have to rely on additional processes (discussion of the concepts “preattentive” and “preconceptual”, as well as of the theoretical mechanism responsible for individuation – the visual indexing mechanism – is reserved for chapter 5).

In contrast with the object-based view of property encoding presented above, many investigators have claimed that detecting the location of an object *precedes* detecting its other properties and is the basis for conjoining or binding different properties together. This is the assumption made by Treisman in her Feature Integration Theory (FIT) (Treisman & Gelade, 1980). There have also been a number of studies (reviewed in Pashler, 1998) showing that in most cases where an object is correctly identified, its location can also be reported correctly, from which it is usually concluded (e.g., Pashler, 1998, p97-99) that location is the basic property used for recovering other feature properties. What all these studies actually show, however, is that when the some property of an object (e.g., shape or color) is correctly reported, its location is usually also correctly reported. This does show that there is a priority ranking among the various properties that are recorded and reported, and that location may be higher on the ranking than other properties. What it does *not* show is that *in order to detect the presence of a feature one must first detect its location*.

In an attempt to provide a more direct test of this hypothesis, (Nissen, 1985) used a conjunction detection task and compared the probability of correctly reporting individual stimulus properties (say shape or color), the location of those properties, and the joint probabilities of the correct report of properties and location. She found that accuracy in reporting shape and color were statistically independent, but accuracy in reporting shape and location, or color and location, were not statistically independent. In fact the

conditional probabilities conformed to what would be expected if the decisions were sequential – i.e., if the way observers detected the presence of a particular conjunction of color and shape is by using the detected (or cued) color to determine a location for that color and then using that location to access the shape.³¹ From this Nissen concluded that detection of location underlies the detection of the conjunction of the two other features, or, to put it slightly differently, that in reporting the conjunction of two stimulus features, observers must first find the location that has both features. This way of interpreting the results is also compatible with how Treisman interpreted the slower search times for detecting conjunction targets. It was assumed that in searching for conjunction targets the location of one of the conjuncts had to be established first and then the location used to find the corresponding second conjunct which had to be done by moving focal attention serially through the display (or at least to all items having the first conjunct property).

But notice that in all studies that examine the mislocation of properties, as for example in the case of conjunction illusions, location and object identity (i.e., *which* object it is) are confounded since the objects have fixed locations: in this case *being a particular object O* is indistinguishable from *being at location X*. Because of this, the findings are equally compatible with the view that individual objects *as such* are detected first, before any of their properties (including their location) are encoded, although among the first properties to be encoded may be the location of the object in some frame of reference. The studies described in Chapter 5 (dealing with multiple object tracking) suggest ways to separate the question of whether an object, as opposed to the location of a feature, serves as the basis for property judgments. Such a distinction requires that we have a more precise sense of what mean by an object, as such, being detected – which I will attempt to do in terms of what I call “indexing” which I will initially tie to the multiple-object tracking paradigm. The notion of indexing (or sometimes “individuating”) is close in spirit to what others have called “marking” or “tagging”. Indexing an object in this sense is independent of whether any of its properties have been detected and encoded. The theoretical position developed in Chapter 5 entails that one can detect, or obtain access to, or *index* an object without encoding any of its properties, including its location. The general position I will defend is that the early visual system possesses a mechanism for detecting and tracking what I will refer to as “primitive visual objects.” It does so by keeping track of them *as individuals* rather than as “whatever is at location X” or “whatever has property Y”. Indeed, we will see that there is evidence that people fail to notice properties or changes in properties of items which they are able to track, thus showing that keeping track of individuality of an object is independent of encoding their properties.

4.5 Visual attention is directed at *Objects*

The original understanding of focal attention assumed that it shares a number of critical properties with direction of gaze. For example, it was generally assumed that although attention may be allocated overtly or covertly, may be allocated in a narrow or diffuse manner, or may be allocated to regions of some particular shape, it is always allocated in a spatially unitary manner. In other words, it is not divided among disparate noncontiguous regions. Moreover, it was also assumed that, like direction of gaze, focal attention is directed in a certain *direction*, or to a certain *region* of the visual field. In addition it was generally assumed that when attention is *focused* it means that processing resources (or at least preferential access to such resources) is made available to the region on which attention happens to be focused. Many of these widely-held assumptions will be challenged in what follows. In particular the following claims will be discussed: (a) the claim that the evidence (some of which has already been discussed) suggests that the focus of attention is in general on certain primitive *objects* in the visual field rather than on unfilled *places*, and (b) the claim that there is a mechanism (which I call a visual index) that is assigned prior to focal attention being allocated, and that individuates objects and allows them to be addressed even before any of their properties have been

³¹ For example, the probability of correctly reporting both the location and the shape of a target, given its color as cue, was equal (within statistical sampling error) to the product of the probability of reporting its location, given its color, and of reporting its shape, given its location – i.e., $P(\text{shape \& Location} \mid \text{color}) = P(\text{shape} \mid \text{color}) = P(\text{location} \mid \text{color}) \times P(\text{shape} \mid \text{location})$.

detected. Claim (b) is the subject of Chapter 5. In what follows discussion will be confined to the first of these claims: the view that focal attention is typically directed to *objects* rather than to *places* and therefore that the earliest stages of vision are concerned with individuating objects and that when visual properties are encoded they are encoded as *properties of individual objects*.

4.5.1 The capacity of the “visual buffer”

It has been known for a long time that even for very short periods of time (less than a second) the amount of information that can be retained is not unlimited. This idea of short-term memory had been investigated for many years (and led to the famous paper on the “Magic number seven...” alluded to in section 4.2) and in general the consensus is that it is limited in the number of units or “chunks” that it can store. However, the application of this idea to visual information had not been investigated in detail. Recently (Luck & Vogel, 1997) took up the question of what corresponds to a “chunk” in vision. They showed that visual short-term memory holds about 4 colors or shapes or orientations or other features of this sort over a brief period of time. Then they asked what would happen if the features to be recalled were associated with a single individual object. They found, rather surprisingly, that a large number of features could be retained so long as the number of individual *objects* was not more than 4. In fact, it seems that one can retain the conjunction of at least four features when they are associated with four different individual objects – or 16 distinct features in all. The fact that visual information appears to be chunked according to individual visual objects suggests that encoding of visual information proceeds by objects, not by feature. This, in turn, suggests that the attentional bottleneck operates over individual objects and that what happens early on in the visual pathway is that objects are individuated or selected. This is an idea that has received considerable and varied support in recent years and I shall examine the evidence in the following sections.

4.5.2 Extracting visual information from within and between objects

The notion that objects are detected and then visual properties are bound to them at a very early stage in visual perception has also received support from many studies showing that it is faster to report several features or properties if they are associated with the same object. Also features that are part of different objects interfere less in a search task. For example, (Duncan, 1984) and later (Baylis & Driver, 1993) showed that access to relational properties of two features (such as “larger than”) is faster when the features in question belong to the same perceptual object than when they are parts of different objects, even when they are the same distance apart.

The original study (Duncan, 1984) sought to control for location as the basis for attention-focusing by superimposing figures at the same location. Using overlapping figures such as those in Figure 4-7, Duncan asked observers to make concurrent judgments about pairs of properties. These properties could both concern one object or they could concern each of two objects. He found an advantage for pairs of judgments made concerning one object compared to two objects. This has become known as the single-object superiority effect, or the two-object cost.



Figure 4-7. Figures used in (Duncan, 1984) to compare the time it takes to report pairs of concurrent judgments based on one object and the time it takes to report pairs of concurrent judgments concerned with two objects. The judgments were: solid vs dashed line, left vs right-leaning, small vs large rectangle and left- vs right-side gap.

The choice of these figures was not ideal in a number of respects. For example since the features do not cover precisely the same region in space, judgments might involve spatially-focused attention. To counter this sort of criticism, (Baylis & Driver, 1993) used figures in which the one-object versus two-object conditions were physically identical and the distinction was one that the observer determined through a voluntary allocation of attention. Examples of the figures Baylis & Driver used are shown in Figure 4-8.



Figure 4-8. Stimuli used to show that access to relational (two-feature) information is faster when the properties pertain to one object than to two. The two figure show are identical shapes which can be parsed as one or two objects depending on whether subjects are instructed to attend to red or green regions (shown here as dark or light gray). The task is to say whether the left vertex is lower or higher than the right vertex. When the vertexes are seen as within one figure the judgment is faster. (Based on Baylis & Driver, 1993).

When observers are asked to attend to the red (inner) figure their judgment of the relative heights of the concave vertices is a within-object judgment, whereas when they are asked to attend to the green (outside) figures their judgment of the relative heights of the two vertices is a between-object judgment. As expected, Baylis and Driver found a faster reaction time when the elements of the judgment belonged to the same object. But as usual, there are refinements and qualifications to such experiments. For example, the “figure” in the two cases investigated by Baylis et al. differ in that the one involved in the single-figure case is convex whereas the ones involved in the two-object case are concave. Is that what makes the difference between the single-object and the two-object conditions? (Gibson, 1994) argued that it does, but (Baylis, 1994) showed that the longer two-object reaction time remains even with equal convexity (row 2 of Figure 4-9). But there are other possible confounds. For example, it is known that focal attention can spread throughout a region (see Figure 4-10 below). (David, Driver, Pavani, & Shepherd, in press) showed that many cases of dual-object feature-report decrements are due to the increased area that has to be examined in the two-object case (an confound that was controlled using the figures on the bottom row of Figure 4-9). But note that when one speaks of the “area” that has to be examined, the assumption remains that it is the area of the *relevant object*, not any area, that matters. So the object-based nature of attention allocation remains generally accepted, even if other factors (e.g. location) may also contribute. Figure 4-9 shows some of the alternative displays designed to counter each of the criticisms.

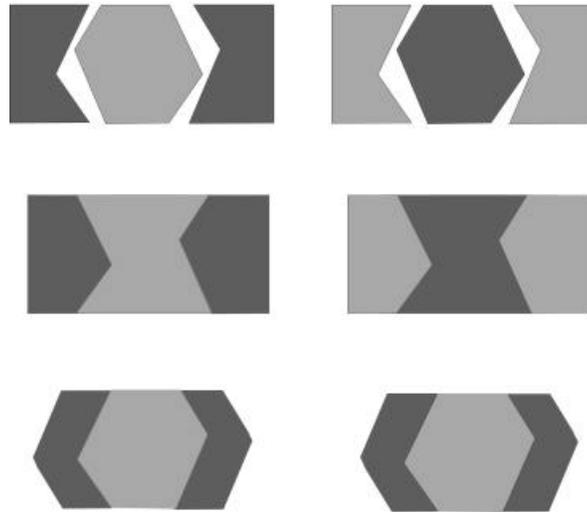


Figure 4-9: Additional figures designed to control for some possible confounds in the original study (Baylis, 1994). The first row shows that observers are able to selectively attend to the single figure in the original study by showing that the same results are obtained with these separated figures. The second row controls for concavity/convexity and the third row controls for overall area.

Another approach to investigating the connection between access to information and objects is to examine the spread of attention using a priming method. Attention appears to spread through a region, and when that happens, the spreads more readily within rather than across objects. For example (Egley, Driver & Rafal, 1994) showed that priming a location increases the detection speed at nearby places and does so more when the places lie inside one object than when they fall across two objects, even when their relative distances are held constant (as shown in the two top illustrations in Figure 4-10). Moreover, (Moore, Yantis & Vaughan, 1998) showed that this is true even when one of the objects is partially occluded – so that the spread follows perceived rather than geometrically-defined regions, as shown in the bottom figures in Figure 4-10.

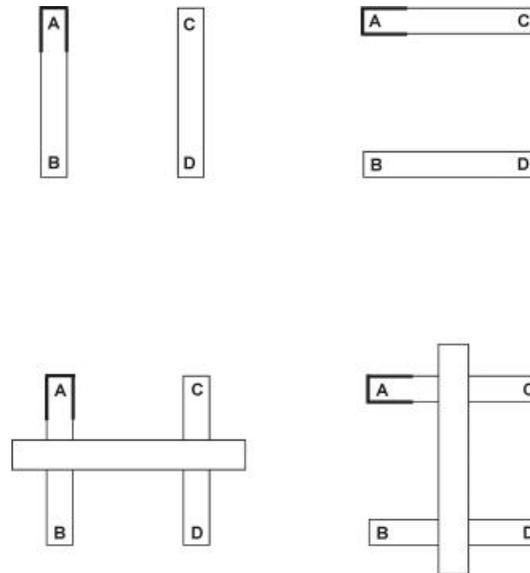


Figure 4-10: The top pair of figures illustrate that when a region such as that marked “A” is primed (by briefly brightening the contour in that region), detection is enhanced in regions within the same object, relative to equidistant regions that lie on another object (based on Egly et al., 1994). The bottom pair of figures (from Moore et al., 1998) illustrates that this holds true even when there is an occluding bar breaking up the region.

The basic idea that attention priming is distributed more readily within objects appears to hold even when an “object” is not confined to a particular contiguous region. For example, (Brawn & Snowden, 2000) found that priming (measured in both detection and discrimination tasks) occurs within each of two overlapping objects (two triangles superimposed to form a “star of David” shape, similar to that illustrated in Figure 4-19). Moreover they found that the effect disappeared when the figure was not perceived as two distinct objects.

4.5.3 Endurance of object-based attention despite changes in the object’s location

A number of different of studies appear to point to the conclusion that the once individuated, the identity of an object – its status as the *same object* – is maintained despite changes in its location or other properties, and even despite certain interruptions in their visibility. One of the first demonstrations of this more robust location-invariant notion of objecthood is a series of studies we carried on multiple-object tracking. Because I now view these studies in a somewhat different light, a discussion of them will be reserved for chapter 5. There was, however, a series of studies described in (Kahneman, Treisman & Gibbs, 1992) that appears to show that both attention and access to the memory record of a visual scene (called an *object file*) is organized in terms of individual objects. Figure 4-11 provides a sketch of a typical object file study. Observers were shown two squares or “boxes” (panel 1). A different letter was briefly flashed in each box. Then the boxes moved around on the screen until each was in a position that was equidistant to the two original box positions (panel 3). A letter then appeared in one of the boxes (panel 4) and subjects had to report the letter as quickly as possible. Although either of the original letters was equally likely to occur in either box, subjects were faster in reporting the letter if it reappeared in the same box. But “same box” has to be defined here in terms of its continuity over time, since the boxes were identical in appearance and their locations were changing. In some studies, the “different” box – the one in which a different letter had been displayed – actually ended up at the same location as the one in which the target letter had been initially displayed. Yet it was the identical-box condition and not the identical-location condition that resulted in faster naming. The obvious conclusion in this case is that it was *being in the same box* that speeded up recognition. This remarkable finding has led to the theory that the presence of an

object in the visual field (in this case each of the boxes) is associated with an *Object File* in which properties of that object are stored (in this case this includes the identity of the letter that was displayed in that box). This study can be viewed as extending the (Baylis & Driver, 1993) demonstration of object-based access to visual information, though now we see that object identity remains the same even when its location changes in certain ways (continuously in this case, but it can also change discontinuously as we will see later in Chapter 5).

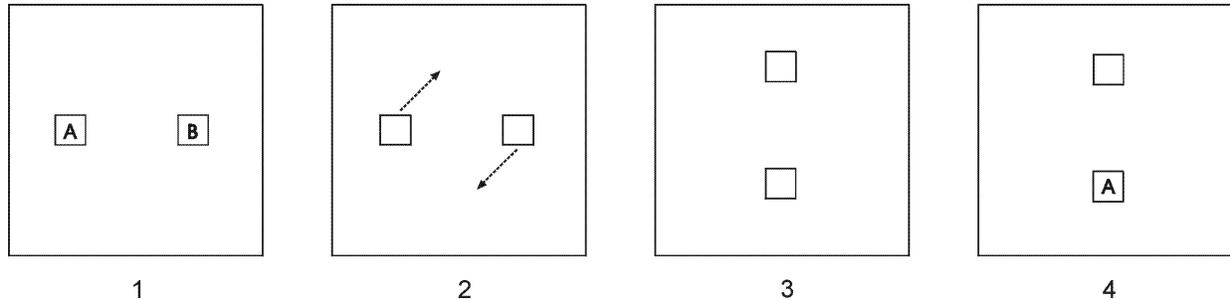


Figure 4-11: Studies showing facilitation of naming of a letter when the letter is in the same box as it was at the start of the trial, even though this was not predictive of which letter it was.

There are many experiments showing that object-based effects travel with moving objects, including ones that use the phenomenon known as Inhibition of Return (IOR) (described in Klein, 2000). Inhibition of Return is the phenomenon whereby it is more difficult for focal attention to be reassigned to a place that had been attended approximately 600 – 900 ms earlier, than to be assigned to a new location. It seems, however, that what is inhibited is not primarily the location, but the object that was at that location, inasmuch as the inhibition travels with the object as the latter moves (Tipper, Driver & Weaver, 1991). Figure 4-12 illustrates this experiment: Here it is the individual cued box rather than its location that appears to be the locus of inhibition (though both can be factors, as was shown in Tipper, Weaver, Jerreat, & Burak, 1994)

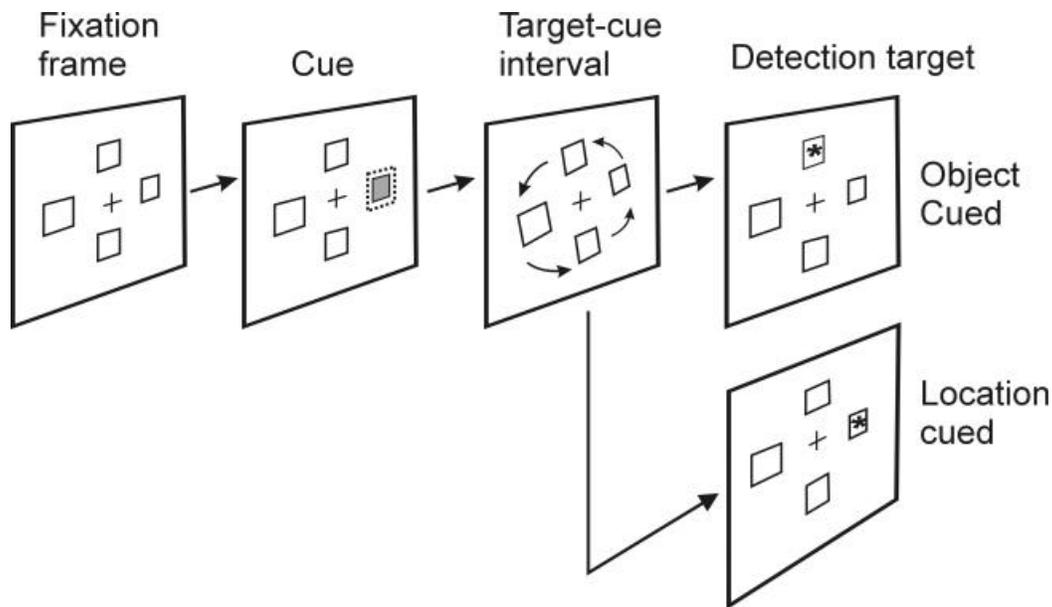


Figure 4-12. Illustration of a display similar to that used by (Tipper et al., 1991) to show that Inhibition of Return (IOR) is object-based. When the target-cue interval is around 600-900 ms it takes longer to detect a small stimulus that occurs on the object that had been cued – even if that object has moved to a different location.

Infants as young as 8 months of age also show object-based effects. (Johnson & Gilmore, 1998) showed that when part of an object was primed and stimuli were presented equidistant from the prime, the infant looked significantly *less* often at the stimulus that was inside the same object as the prime than at the stimulus inside the other object. Although no single-object advantage was found with the particular stimuli used in this study, the results do show that entire objects were subject to an inhibitory or satiation effect in young infants.

4.5.4 Endurance of object-based attention despite temporal interruption

Another clear illustration of the endurance of objecthood is provided by (Yantis, 1995; Yantis, 1998; Yantis & Gibson, 1994) who showed that object individuation not only withstood changes in the object's location, but under certain conditions could also endure despite a brief but total disappearance of the object from view. Yantis & Gibson argued that an object that suddenly disappears and then is followed by an object that suddenly appears in the same location can be interpreted by the visual system as either the same object or as a new object, depending on certain conditions. For example if there is a very short time between the disappearance and reappearance, the visual system treats them as the same object. If the time delay is increased they may be treated as different objects. Figure 4-13 illustrates this point. It shows a pair of dots displayed in sequence in an ambiguous display known as the Ternus configuration. The leftmost object in the bottom pair is located in the same place as the rightmost object of the top pair, but separated by some time delay. When the delay is about 50 ms or less the middle dot is seen as remaining in place while the end one jumps over it: This is called the single-element motion condition. When the delay is 100 ms or longer the pair of dots are perceived as moving from left to right: This is the group-motion condition. Yantis and Gibson argued that the difference is that for short time intervals the middle dot is perceived to remain in place continuously so does not take part on the apparent motion. But when the interval is longer this dot is seen as disappearing and reappearing and hence is perceptually a different object in the two displays, which favors the perception of group motion. But even at relatively long time intervals of absence the dots may, under certain conditions, be treated as the same object. Yantis and Gibson showed that if an apparent occluding surface is inserted during the interval (as shown in Figure 4-13) then even at the longer time interval (when one normally gets group-motion) single-element motion is perceived. Their explanation

is that when an occluding surface is perceived as hiding the middle object, then the object is perceived as persisting throughout the interval, even though briefly hidden by the occluding box. Under those conditions the display acts like the short-duration display since the middle dot is not seen as disappearing and being replaced by a new object, but rather as being briefly hidden by an opaque surface.

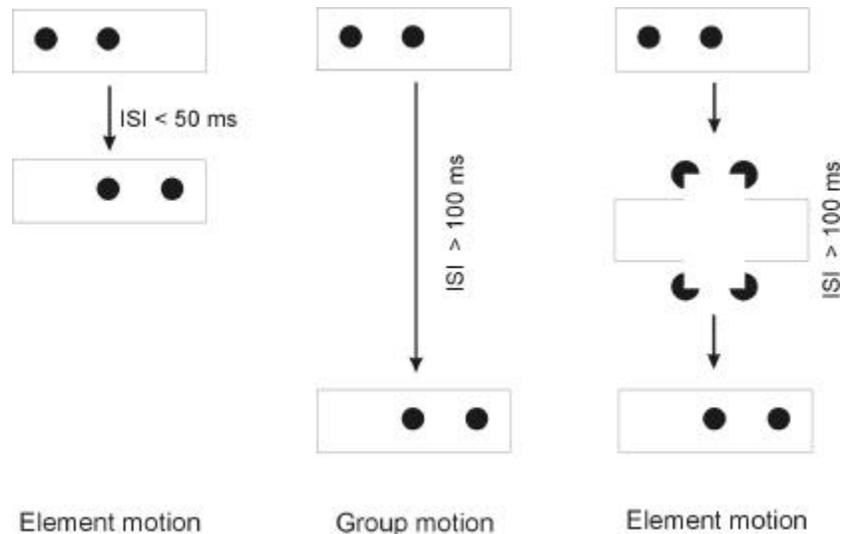


Figure 4-13: The Ternus display. When the delay is short (inter-stimulus interval less than about 50 ms) the middle dot is seen as remaining in place and the outside dots are seen to jump over it (single element motion). When the delay is long the middle dot is seen to disappear and a new one appears in its place, resulting in “group motion” (where the two dots are seen as moving together). On the right is the display described in (Yantis & Gibson, 1994). Here the durations are the same as in the center figure, but the appearance of a “virtual opaque rectangle” during the interval “explains” the apparent disappearance of the middle dot, so the percept is that of element motion as in the left figure.

In chapter 5 we will see other examples of the persistence of object-identity through changes in other properties and also through longer periods of disappearance from view – though we will also see that the latter only occurs under conditions which, like the Yantis and Gibson example discussed here, provide cues to the presence of an occluding surface. These cases involve the multiple object tracking studies that I discuss at length in Chapter 5.

4.5.5 Object-based attention when “object” is not defined spatially

The most direct test of the idea that the single-object superiority effect does not require spatially distinguishable objects was reported by (Blaser, Pylyshyn & Holcombe, 2000a; Blaser, Pylyshyn & Holcombe, 2000b). Blaser et al. used two superimposed disks of bars called Gabors. Gabors are patches of sign-wave modulated color or intensity stripes that fade off at the edges according to a Normal or Gaussian distribution. Each of the two superimposed Gabor patches varied continuously and independently in spatial frequency, orientation and color. By rapidly alternating the two slowly-changing Gabor patterns, a display was created in which the pairs of figures are perceived as two overlapping transparent layers that change individually rather than as a single changing plaid texture. Figure 4-14 shows a sequence of such Gabor patches, rendered in black and white instead of the original color. Blaser et al. showed that such “objects” could be successfully tracked over time even though they do not move in spatial coordinates but “travel” through a three-dimensional “property space” as shown in Figure 4-15. Blaser et al. also showed that performance in detecting discontinuities in pairs of properties (e.g. sudden small jumps in orientation and color) was better when the discontinuities occurred on the same “object” than when they occurred on different objects, even though in this case the “objects” are perceptually defined in terms of their continuous motion through the property-space. This demonstrates that whenever some set of properties is perceived as

a unitary whole the resulting whole has many of the properties of a perceptual “object” insofar as it can be tracked through continuous changes (in properties, not in space) and shows single-object superiority effects. It appears, therefore, that “objecthood” need not be defined in terms of spatial coherence or spatiotemporal continuity. This lends further support to the notion that in general the detection of objecthood need not proceed by the prior detection of location, or by the detection of property-P-at-location-X, where the property P and the location X are part of the initial encoding.

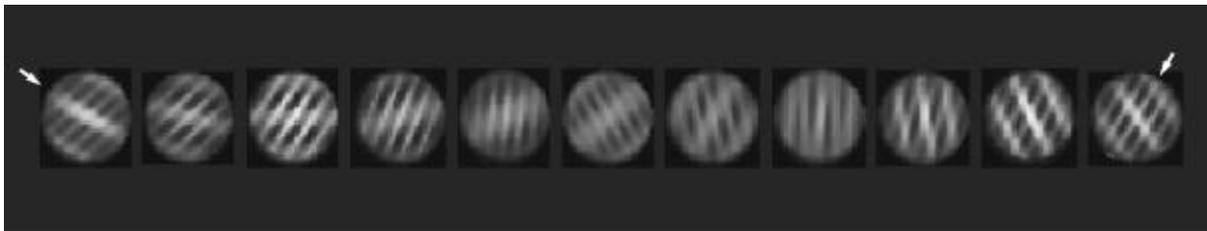


Figure 4-14. This figure shows a sequence of snapshots, taken every 250 ms, of overlapping, slowly changing pairs of Gabor patches, (they are shown here side-by-side and in monochrome gray, rather than in the original two color presentations varying in time). The superimposed transparent pairs are tracked as two slowly changing individual “objects”. Observers were able to indicate which of the two overlapping Gabors patches had initially been designated as “target” (based on Blaser et al., 2000b).

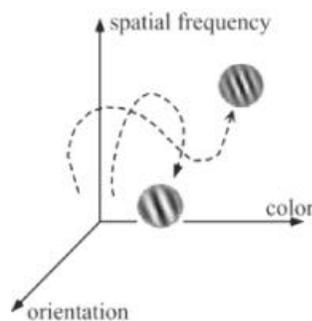


Figure 4-15. Graph of the above sequence showing it as moving through a three-dimensional “property space,” while remaining fixed in spatial coordinates.

4.6 Neural bases and neuropsychological evidence for object-based information access

4.6.1 How do the ventral and dorsal visual systems coordinate information?

There has also been considerable interest in recent years in what have been called “two visual systems”. (Ungerleider & Mishkin, 1982) claimed that there are two streams of visual processing in the brain: A dorsal stream that encodes *where* a thing is and a ventral stream that encodes *what* it is (its identity, in terms of some category stored in memory). Although it now appears doubtful that “where” and “what” are the proper way to characterize these two systems (for example, Milner & Goodale, 1995, have made a strong case that the ventral system is best characterized as concerned with recognition while the dorsal system is concerned with the visual control of action), it remains generally accepted that the location in space of various features is computed relatively independently of their configuration or what they are recognized as. But if this is true, then the question immediately arises: *What* does the dorsal system compute the spatial location *of*, if it does not know *what* is at that location? A reasonable answer is that it computes the location of whatever it is attending to. Since there is reason to think that what the visual system attends to are objects, we might expect that both systems share an interest in properties of *objects*.

However one characterizes the two visual systems it is clear that they must interact. In fact (Duncan, 1993) has shown that this interaction can result in interference between judgments based on where and those based on what. Duncan showed observers displays, such as those shown in Figure 4-16, each of which had two “objects” that are briefly displayed in unpredictable locations (an “object” consisted of 4 dots and a grid of parallel lines) and asked them to make two concurrent judgments. The two judgments could concern either the same object or different objects, and could either involve the same visual system or different visual systems (i.e., they might both concern location – such as which is to the left or above – or both concern some visual feature – such as the spacing, orientation, or length of the gridlines). Results showed that pairs of concurrent judgments made across different objects experienced strong interference, whether they involved the same or different visual systems. No interference between the two visual systems was observed, however, when both judgments concerned *the same visual object*. Duncan concluded that “the separate outputs of ‘what?’ and ‘where?’ processes can be used concurrently without cost, but only when they concern the same object. (p 1269)” which suggests that coordination occurs at the point after objects have been individuated and attended.

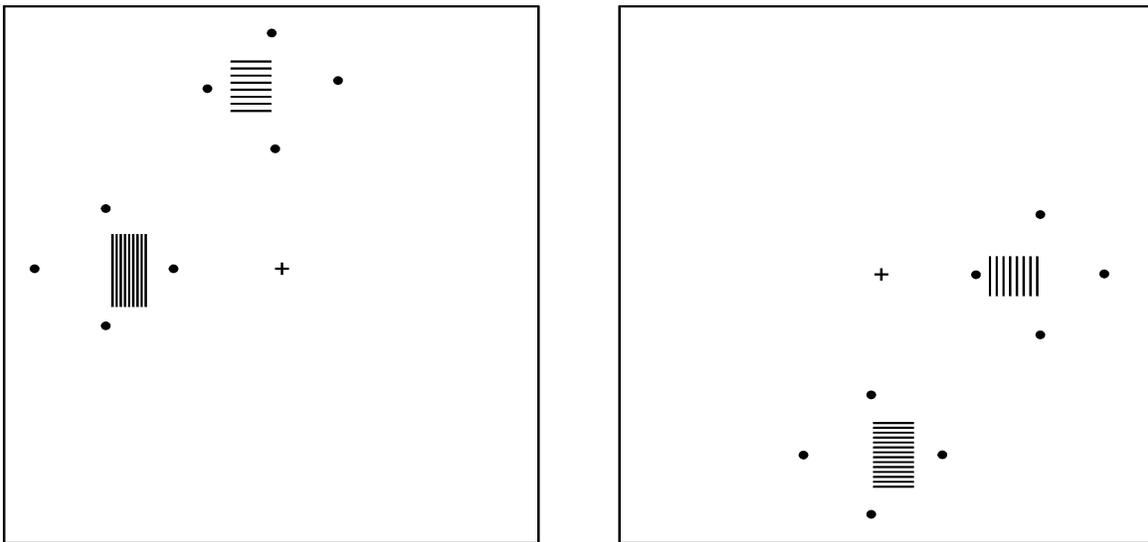


Figure 4-16. Two displays such as those used by (Duncan, 1993) to examine availability of “what” and “where” information from within one object and across two objects. Here “objects” are clusters of 4 dots and one grid, location information is assessed by a judgment of whether the grid is left or right or above or below the center of the object, and feature information is assessed by a judgment of high vs low spacing, long vs short grids and horizontal vs vertical orientation.

Neuropsychological evidence for the importance of the object-individuation stage in vision comes from a number of characteristic dysfunctions of attention, chief of which is hemispatial neglect and the Balint syndrome, discussed below.

4.6.2 Visual Neglect

Visual neglect or hemispatial neglect is a disorder that often went undetected in the past, but has received a great deal of attention in recent neurological studies (see the review in Rafal, 1998). So-called “visual neglect” patients, who usually have lateralized parietal lesions, appear to neglect information on the side of their visual field contralateral to their lesion. For example they exhibit such symptoms as failing to eat food on half of their plate, failing to draw details of half of a scene, and even failing to dress half their body. Recent evidence has suggested that rather than neglecting half of their visual field such patients may neglect half of visual objects, regardless of the visual field in which the objects are presented – in other words neglect may often be object-based. For example, (Behrmann & Tipper, 1994) tested left-neglect patients on a task that required that they detect targets in ‘dumbbells’ consisting of two circles connected by

a line. These patients were slower to detect targets presented on the left side of the dumbbell, as expected. But when they saw the dumbbell rotate through 180 degrees, they were then slower to respond to targets presented on the *right* side of the dumbbell. (Tipper & Behrmann, 1996) also showed that this reversal only occurred with connected pairs of circles (i.e., dumbbells), which were treated as a single object. When the line connecting the two circles was removed, subjects were always slower to respond to targets on the left side of the display, regardless of how they moved about. This suggests that these patients do not neglect half of their visual field (i.e., half of ego-centric space), but rather half of individual objects. In other words it appears that in this case the frame of reference that characterizes their neglect is object-based, so that when the object is rotated by 180 degrees the basis of their neglect rotates with it, resulting in the right side of the visual field (which now contains what was initially the left side of the object) becoming the neglected side. (Behrmann & Tipper, 1999b) also showed that object-centered and body-centered neglect could occur at the same time. When stationary squares were added to the dumbbell display, as in Figure 4-17, patients simultaneously neglected the stationary square on the left side of the display, and the rotated dumbbell on the right side. This suggests that neglect can simultaneously operate in multiple reference frames. Body-centered neglect and object-based neglect may also interact. Thus, for example, the primary axis of an off-vertical object may serve to *define* egocentric left and right for an observer, such that neglect might still be considered as a primarily egocentric disorder, but with object-based contributions to the egocentric axis (e.g. Driver, 1998; Driver & Halligan, 1991). Other findings of object-based effects in visual neglect (and related disorders) are reported by (Driver, 1998; Driver, Baylis, Goodrich, & Rafal, 1994; Driver & Halligan, 1991; Rafal, 1998; Ward, Goodrich & Driver, 1994). (Egly et al., 1994; Humphreys & Riddoch, 1994; Humphreys & Riddoch, 1995) have also used neglect patients to explore attentional selection within and between objects.



Figure 4-17: Left visual neglect patients respond more quickly when detecting a brightening of the objects on the right of their visual field. But if dumbbell-shaped object-pairs are used and are rotated while being observed, these patients will respond faster to the circle on the left – the one that had previously been on the right. If an unconnected pair of squares is also present the one on the right of this pair continues to receive preferential responding (as shown by the dots around the figures), thus illustrating simultaneous object-based and egocentric-based neglect (based on Behrmann & Tipper, 1999b).

4.6.3 Balint Syndrome

Additional neuropsychological evidence for the object-based nature of visual attention comes from the study of Balint Syndrome patients, in which patients with parietal lesions (usually bilateral) exhibit surprising object-based deficits (see the review in Rafal, 1997). Balint Syndrome patients, who typically have bilateral parietal lesions, exhibit many different types of deficits, which may not all share a common cause. These deficits include near-complete spatial disorientation (including the inability to indicate an object by pointing or even by verbal description), abnormal eye movements, optic ataxia (a disorder of visually-guided reaching), and impaired depth perception. One of the most remarkable components of Balint Syndrome, however, referred to as *simultanagnosia*, is the inability to perceive more than one object at a time, despite otherwise normal visual processing, including normal acuity, stereopsis, motion detection, and even object recognition. Patients with this type of deficit fail even the simplest of tasks that requires them to judge a relation between two separate objects (Coslett & Saffran, 1991; Holmes & Horax, 1919; Humphreys &

Riddoch, 1993; Luria, 1959; Rafal, 1997). The object-based nature of the Balint syndrome (and especially of simultanagnosia) was noted many years ago. Studying brain injuries after the first world war, (Holmes & Horax, 1919) noted that although Balint patients were unable to determine if two parallel lines were of equal lengths (as on the left of Figure 4-18), they could tell whether a simple shape was a rectangle or a trapezoid (as on the right of Figure 4-18), even though in the latter case the same two lines were simply connected to form a single shape. What seemed to matter was whether the judgment involved what the person saw as one or as two visual objects.



Figure 4-18: Simultanagnosic patients have trouble judging whether the pair lines on the left are equal, but find it easy to judge that the figure on the right is a trapezoid and not a rectangle. Although both involve judging the same pair of lines, in the case on the right they are part of a single object (from Holmes & Horax, 1919).

In classical simultanagnosia, patients are typically unable to see two separate items (e.g. circles) simultaneously, yet they are able to see a single dumbbell made up of the same two circles (Humphreys & Riddoch, 1993; Luria, 1959). It was even noted (Luria, 1959) that object-based percepts did not have to be localized, so that if the two overlapping triangles, composing a ‘Star of David,’ were colored separately so they could be distinguished and attended individually, simultanagnosic patients would often perceive only one of them. The existence of simultanagnosia as a syndrome confirms once again that vision and visual attention operate over units that I have informally referred to as visual objects.



Figure 4-19. A two-colored star. Some simultanagnosic patients only see one triangle – though which one they see may switch over time as they move their attention about.

4.7 What is selected in visual attention?

It appears, then, that a variety of sources of evidence strongly suggest that attention (as well as “inattention”) operate – at least in part – on whole objects, rather than on places or regions or any other spatially-defined entities. Such visual attention may be allocated voluntarily by an observer who wishes to devote special processing capacity to the object, or it may be attracted exogenously and automatically by events in the visual scene. Among the deeper puzzles that remain is: What happens to the information that is not selected? Some evidence suggests that after a brief delay it is simply lost. But other evidence suggests that it may have a lasting effect even though it cannot be explicitly recalled. This effect can be either positive (as when recognition of the unattended information improves or “primes” subsequent

recognition of related stimuli) or negative (as when it subsequently takes longer to respond to stimuli that are related to the unattended stimuli). The exact conditions under which one observes positive priming, negative priming or simply neglect of unattended information, are not well established. Nonetheless there appears to be converging evidence that whatever focal attention does, it appears to deal with entire objects (or sometimes with distinct parts of a larger object).

Because focal attention can be allocated voluntarily, based on what the perceiver is trying to detect or to recognize, it provides one of the few mechanisms by which cognition can influence visual perception, as we saw in Chapter 2. When perceptual learning occurs it is almost always the case that what is learned can be formulated in terms of what aspects of a scene the person learns to attend to or to give processing priority (an extreme case of which is when people learn *where to look* – as in the chicken-sexing example discussed in section 2.5.3.2).

In the next chapter we will see that the idea that attention is object-based has far-reaching implications for how the visual system makes contact with the perceived world. That's because object-based attention depends on being able to compute when two distinct visual elements arise from the same individual object in the world. The fact that visual attention is object-based and the objects it focuses on are enduring ones (as suggested in section 4.5.3) means that visual attention succeeds in computing same-objecthood or, to put it another way, the object-individuation mechanism discussed earlier is indifferent to the location or other visual properties of the objects: It tracks individuals *qua* individuals and thus repeatedly solves a problem that has become known as the “correspondence problem.”

5. THE LINK BETWEEN VISION AND THE WORLD: VISUAL INDEXES

In this chapter I describe a theory of a certain mechanism in early vision that is related to focal attention but is more primitive and operates earlier in the information-processing stream. The theoretical idea, which I have developed over the past 15 or more years, is called *Visual Index Theory*. It postulates a mechanism, called a visual index (sometimes referred to as a FINST – see Note 33), that precedes the allocation of focal attention and allows the cognitive system to pick out a small number of what I will call *primitive visual objects* or *proto-objects*, in order subsequently to determine certain of their properties (i.e., to evaluate certain visual predicates over them, perhaps by “probing” or interrogating them). The theory is based on the recognition that in order to allocate focal attention, or to do many other visual operations over objects in a display (e.g., encode their spatial relations, allocate focal attention to them, perform an eye movement to them), it is first necessary to have a way to *bind* parts of representations to these objects. A less technical way to put this is to say that if the visual system is to do something about some visual object, it must in some sense know *which* object it is doing it *to*. This applies equally whether the activity is detecting a property, making a judgment, or recognizing a pattern among certain objects in the field of view. Detecting a certain property is of little use unless that property can be associated with or assigned to something in particular in the perceived world: Properties are predicated of *things*, and relational properties (like the property of being “collinear”) are predicated of several things. So there must be a way, independent of the process of deciding which property obtains, of specifying which objects are being referred to.

The usual assumption about how objects can be referred to is that they are referred to by some unique property that they have – in the most general case by their *location*. But there are empirical reasons to reject this view, some of which have already been discussed in the previous chapter, in connection with the evidence that attention is allocated to *objects*, and that the location of an object is independently detected, like any other property of the object. I take the view that *objects* are indexed directly, rather than via their properties or their locations.³² The mechanism for binding visual objects to their representations is called a *visual index*. We will see later that this approach finds unexpected support in several disparate areas, including research into the cognitive capacity of infants as well as philosophical writings concerned with special ways of referring called *indexicals* or *demonstratives*. I will return to these issues when I examine the wider theoretical and philosophical implications of our approach. For now I will concentrate on the empirical arguments that derive from the study of visual attention, and which lead us to postulate the FINST binding mechanism. I begin by offering a description of the indexing idea and the motivation behind it.

5.1 Individuating primitive visual objects: Visual Index (*FINST*) Theory

As a matter of history, the original context in which the present ideas developed was that of designing a computer system that could reason about geometry by drawing diagrams and “noticing” properties in these diagrams (some of this work is described in Pylyshyn, Elcock, Marmor, & Sander, 1978). It soon became clear that it was unreasonable to assume that the entire fully detailed diagram was available in the visual representation, for reasons such as those discussed in Chapter 1. So it seemed that the actual diagrams would have to be scanned by moving the fovea around to different parts of the diagram. Consider a diagram such as shown in Figure 5-1, which may be drawn while proving some theorem or merely looking for some interesting properties of a construction.

³² Note that this is independent of the question (discussed in the last chapter) of whether or not attention can be directed to locations as well as to objects. It is possible that attention can be moved through empty space, and therefore to fall on unoccupied regions of the visual field, and yet for location to play no special role in the individuation and detection of objects. Indeed, it is even possible (and very likely) for the relational property “being at a different location” to play a central role in *individuating* objects without the actual locations playing a role in determining their identity or having a special role relative to other properties that are encoded for particular objects. See section 5.4 for an example of different properties being used for individuating and for identifying.

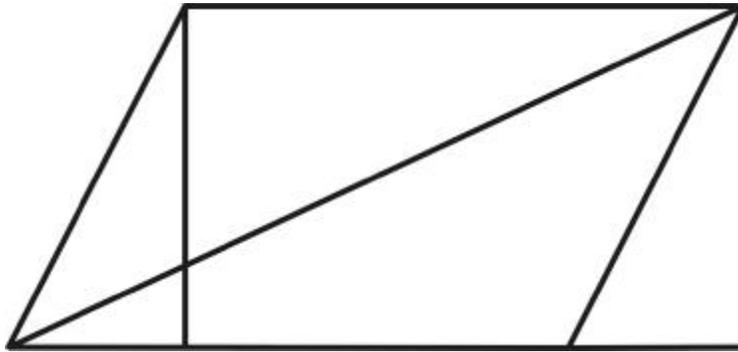


Figure 5-1. An example of a figure that might be drawn in the course of a geometrical reasoning task.

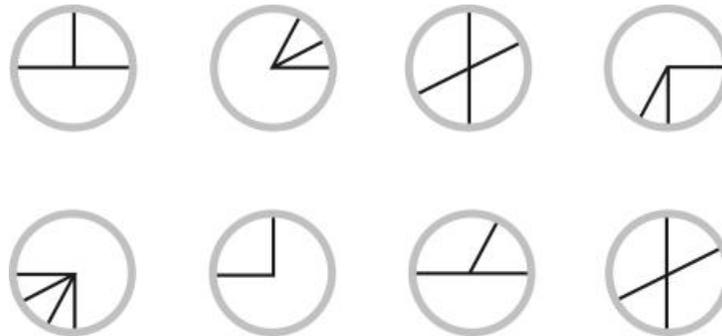


Figure 5-2. An example of the kinds of partial glimpses one might have in the course of examining Figure 5-1.

If the figure is explored over successive glances, or even just over a stretch of time while various properties are noticed, there immediately arises the problem of maintaining a correspondence between objects seen on successive glances (as in Figure 5-2) as well as between parts of the diagram and an evolving representation of the figure. The latter representation might even contain such non-geometrical information as what the person had *intended* to draw (diagrams have to be viewed in terms of idealizing concepts like “line”, “side of a triangle” or “bisecting angle” and so on, irrespective of exactly how accurately the diagram was drawn) as well as the interpretations already placed on the diagram by earlier perceptual analyses. In addition there is the problem of recognizing parts of the diagram visited earlier in the scanning – i.e., cross-visit correspondences would have to be maintained in some way. One obvious way to maintain these correspondences is to assign a unique description to parts that needed to be placed in correspondence, and then to match descriptions each time a new view was recorded. At minimum this would have required keeping a rich and detailed representation of parts of the diagram – an unrealistic assumption and one that is very unlikely to be true of the human visual system (for reasons discussed in Chapter 1 and below). These problems led to the postulation of the original idea of FINSTs as a type of index or virtual finger³³ that kept track of particular parts of the diagram currently in view and bound them to the drawer’s intentions and to a partial description already constructed from previous visits. The more general need for a mechanism such as an index became clearer as we considered what was involved in

³³ This (perhaps unfortunate) acronym, derived from “FINgers of INSTantiation” arose because we initially viewed this mechanism in terms of the metaphor of keeping “fingers” on certain objects, which made it possible to direct inquiries to them or to move attention to them. If you imagine the cartoon character “Plastic Man” sticking long flexible fingers on a number of objects, and imagine that the fingers themselves cannot sense any properties of these objects but can allow the individuated objects to be queried by attending to them, this captures the basic idea behind visual indexes. The term “instatiation” connotes the use of the indexes to bind mental particulars (or symbols) to objects, which then “instantiates” the variables. But all that is (mere) historical footnote; the notion has since gained its own footing in the context of investigating multiple foci of attention and access.

recognizing extended patterns involving several distinct glimpses. At least for certain tasks, the visual system must have some mechanism for picking out particular elements in a display in order to decide whether they have certain properties (as in the Treisman rapid search experiments described in Chapter 4) or to decide whether two or more such elements form a pattern, such as being *collinear*, or such as an element being *inside*, *on*, or *part of* another element, and so on.

Shimon Ullman (Ullman, 1984) refers to the process by which such relational properties are computed as “visual routines”, and has argued that the recognition of certain visual patterns requires, by the very nature of these patterns, that a serial process be deployed which accesses or scans the display in certain ways, visiting the elements in question in a serial fashion. But the question that immediately arises is how the visual system designates or picks out the objects that the visual routines visit or over which the visual routines compute properties. The problem is even deeper than merely finding a unique way to specify which items the visual routine must visit, for suppose the visual system succeeds in detecting the patterns *inside* or *same-contour* in Figure 5-3. How does it specify which particular things or graphical elements these relations are true of? This is a non-trivial problem because it will not do to simply assert that the relation holds in the figure – it must hold of particular individual *token elements* in the figure. Asserting that it holds of elements meeting a particular unique description also will not do in general, as we will see in detail later in section 5.3. What the visual system needs is a way to refer to individual elements *qua* token individuals. Ullman, as well as a large number of other investigators (e.g., Ballard, Hayhoe, Pook, & Rao, 1997; Olivers, Watson & Humphreys, 1999; Theeuwes, A.F. & Atchley, 1998; Watson & Humphreys, 1997, 1998; Yantis & Jones, 1991) talk of the objects in question as being “tagged” (indeed, “tagging” is one of the basic operations in Ullman’s theory of visual routines). The notion of a tag is intuitively appealing since it suggests a way of placing a unique mark on individual objects for reference purposes. A tag provides a means for referring to objects, somewhat like *naming*, except that it suggests two very desirable properties that, in fact, will form part of the motivation for developing the Visual Index theory. The properties that the idea of a tag suggests (though does not quite achieve) are: (a) the reference is only active while the object is in view and (b) there is a sense in which the responsibility for maintaining the reference link is externalized – the link is maintained because of the external tag and not because the visual system searches for particular objects by remembering unique properties of those objects, including where they were located in the visual field. Yet the notion of a tag is also misleading for a number of reasons. One of the purposes of a tag is to allow the visual system to revisit the tagged object in order to encode some new property (as is explicitly assumed in the Hayhoe, Bensinger & Ballard, 1997, theory). Thus it does no good to place the tag on an item in the *representation* of the scene since revisiting the representation does not, in general, allow new visual properties to be discovered. This is true even if the representation was pictorially exhaustive. Such an exhaustive representation is implausible on information-theoretic grounds and also, as we saw in Chapter 1, on empirical grounds. In any case this option would not allow the tagged item to serve as a target for either attentional scanning or eye movements, since one does not move one’s attention or one’s gaze to a representation of an object but to the real object in the world.

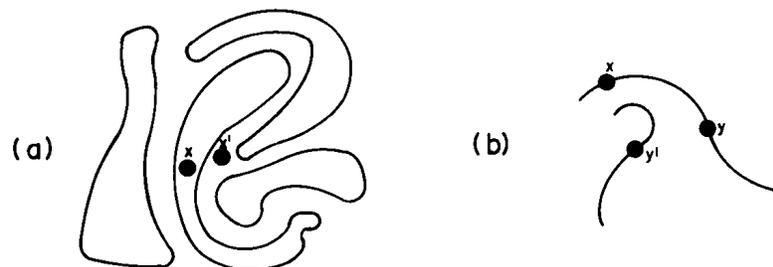


Figure 5-3. Examples of properties that (Ullman, 1984) suggests require serially applied “visual routines” for their detection. In (a) the property to be detected is whether a dot (either x or x') is *INSIDE* a closed contour. In (b) the property in question is whether the pair of dots x and y (or x and y') are on the *SAME-CONTOUR*.

Our indexing proposal is a hypothesis concerning a possible mechanism for “picking out,” or “individuating,” distal objects in order to allow further visual properties of those objects to be detected or to allow motor actions (such as eye movements) to be directed to them. Thus it’s more like the proposal that objects in the *world* are “tagged” in some way. Of course unless we can write on the real objects in the world, this cannot be literally what happens.³⁴ But something close to a functional tagging can be accomplished by a mechanism related to focal attention. In what follows I will describe this proposal and show that this type of mechanism not only has ramifications for how cognition is connected to the perceived world, but it also has considerable empirical support as we will see.

The *Visual Index* idea is closely related to Kahneman & Treisman’s *Object Files* (Kahneman et al., 1992), described briefly in section 4.5.3, except that visual index or FINST theory emphasizes the mechanism that connects the representation with the objects in question.³⁵ Despite the simplicity of the indexing idea, it sometimes gets complicated in the explaining because it requires making a number of distinctions that are conflated in such everyday terms as “tracking”, “recognizing”, “identifying”, “locating” and so on. I will try to develop the relevant distinctions by sometimes introducing narrower technical terms and by trying to make the same points in a number of different ways.

The assumptions that form part of the theory are listed in Table 5-1 for easy reference. This list emphasizes, in outline, how the mechanism might work, rather than the function it computes. This (as well as the further discussion in Section 5.5 and the Appendix) is laid out here to ward off concerns that a mechanism whose essential purpose is to *refer to* individual distal object tokens, leaves us in the dark about how such a function could possibly be implemented. In much of what follows I will concentrate on the role that this indexing mechanism plays in providing a causally mediated referential connection between mental entities (i.e., concepts) and things in the world.

³⁴ Even a literal labeling of distal objects would not help, since we would then need to search the scene for a particular label or else remember which object had which label, which would again require us to be able to refer to distal objects. For example if you needed to move your eyes back to a certain vertex in Figure 5-1 that you remember as being labeled, say “A,” you could not directly move your eyes there but would first have to search the entire figure to find the label, which does not appear to be what actually happens – e.g., (Hayhoe et al., 1997).

³⁵ The relation between *Visual Index Theory* and *Object File Theory* is not entirely transparent due to the fact that the two theories arose in somewhat different contexts. Although they deal with similar phenomena, Object File theory has emphasized memory organization and its relation to the objects from which the information originated. In that respect it is similar to Morton’s “Headed Records” theory of memory organization (Morton, Hammersley & Bekerian, 1985). Indexing theory, on the other hand, arose from the need for a mechanism to keep track of pre-conceptual (or unanalyzed) visual elements in order to keep them distinct and to attach information to them as such information becomes available. Consequently, Indexing Theory emphasizes the mechanism required for establishing and maintaining the connection between objects in the visual field and mental constructs (representations) of them. The discussion of the difference between individuation and recognition later in this chapter, as well as the experiments to be described in Sections 5.2 and 5.4 below should help make this difference in emphasis clearer.

Table 5-1: Some Provisional Assumptions of Visual Index (FINST) Theory

- (1) Primitive visual processes of early vision segment the visual field into something like feature-clusters automatically and in parallel. The ensuing clusters are ones that tend to be reliably associated with distinct token individuals in the distal scene. The distal counterparts of these clusters are referred to as *primitive visual objects* (or sometimes just as *visual objects*), indicating our provisional assumption that the clusters that play a role in this theory generally correspond to the proximal (i.e., retinal) projections of physical objects in the world.
- (2) These clusters are activated (also in parallel) to a degree that depends on such properties as their distinctiveness within a local neighborhood, including their temporal (e.g., onset) properties.
- (3) Based on their degree of activation, these clusters compete for a finite pool of Visual Indexes (or FINSTs). These indexes are assigned in parallel and primarily in a stimulus-driven manner. Since the supply of Indexes is limited (to about 4 or 5), this is a resource-limited process.
- (4) Although assignment of indexes is primarily stimulus-driven, there are certain restricted ways in which cognition can influence this process through voluntarily assigned attention. For example, attention might be serially allocated to items with certain discriminable properties, and an index may get assigned to objects selected in this way. (I will return to this question in section 5.2.2).
- (5) An Index keeps being bound to the same visual object as the object changes its properties, including its location on the retina (within certain limits). In fact this is what makes it the “same” visual object. On the assumption that proximal clusters are reliably associated with real distal objects (objects in the world), the indexes can then functionally “point to” objects in a scene without identifying what is being pointed to.
- (6) It is an empirical question what kinds of (proximal and distal) patterns can be bound by indexes. Patterns need not be spatially local and punctate, although patterns larger than the fovea are unlikely to be indexable. Current evidence also favors the view that the onset of a new visual object is an important index-grabbing event. Perhaps the appearance of a new object within focal attention is another type of event that results in the binding of an Index (as in assumption 4).
- (7) Only indexed tokens can enter into subsequent cognitive processing: e.g., relational properties like *INSIDE(x,y)*, *PART-OF(x,y)*, *ABOVE(x,y)*, *COLLINEAR(x,y,z)*,... can only be encoded if tokens corresponding to *x*, *y*, *z*,... are indexed.
- (8) Only indexed tokens can be the target of an action, such as the action of moving gaze or focal attention to it.

Visual indexes were initially introduced to allow vision to access multiple visual objects at one time, and to provide a primitive pre-conceptual causal connection between objects in the world (through their projections onto retinal patterns) and objects of thought (e.g., tokens of mental symbols). However, the theory itself entails certain more general views about how vision connects with the world that I will discuss later in this chapter.

One major motivation for our initial postulation of indexes is related to assumption (7) above. Before any visual object can be identified, it must first get *picked out* from the rest of the visual field and its identity as an individual maintained or tracked over movements of the pattern across the visual field. Our proposal claims that this is done directly by binding some of individual objects through indexes, *not* by identifying the object in terms of a description (including one that refers to its location). What distinguishes the object as an individual, separate from the other features in the scene, is a purely causal sequence of events beginning with some property or combination of properties of the scene and eventuating in an index being grabbed from a pool of potential indexes. Until some piece of the visual field gets segregated or “picked out” in this way, no visual operation can be applied to it since it does not exist as something distinct from the entire

field. Thus in order to recognize or otherwise analyze a visible object in the world it must first be distinguish as a primitive visual individual, separate from the other clutter in the visual field. Without that we would not be able to attribute any properties we had discerned to the thing that had those properties. There would be no “x” to which we could predicate some visual property $P(x)$.

According to the theory, this particular sort of “picking out” and indexing is essentially a causal rather than cognitive or conceptually-driven process and is not mediated by a description or by an encoding of the properties of the things picked out in this way. Recall that in a geometrical reasoning task, the fovea moves around over the diagram, requiring that we keep track of elements that had been seen before (as illustrated in Figure 5-1 and Figure 5-2). The idea is to do so without having to re-recognize features using a stored description. But how can we track something without re-recognizing it as the same thing at distinct periods of time, and how can we do that unless we know what properties it has (i.e., unless we have a description of it)? This is where the idea of tracking as a primitive operation arose. Just as the separation of figure from ground is a primitive function of the architecture of the visual system (at least under some interpretations of the Gestalt notion), so also is tracking. What I propose is not a full-blooded sense of identity-maintenance, but a sense that is relativized to the basic character of the early visual system. In general we cannot re-recognize objects as being *the same individuals* without some descriptive apparatus. But I claim that the visual system *can* track visual objects in a more primitive sense, by treating what is picked out as the same token primitive visual object, so long as certain conditions are met. For example, so long as it follows a certain kind of (perhaps smooth) space-time trajectory, the nature of which is given by the structure of the visual apparatus (and which remains to be discovered by experimental investigation). In Section 5.2.1 I will have more to say about some constraints on being able to keep track of primitive individual objects.

The idea that *indexes* pick out objects without encoding their properties is consistent with findings of studies that explicitly ask what information is stored with an object [i.e., that is stored in what \Kahneman, 1992 #827, referred to as an “object file” – see the discussion in section 4.5.3]. For example, (Gordon & Irwin, 1996) used a priming paradigm to explore whether a moving object carried with it information about the shape, location, semantic feature or category membership of the token object. They presented words and examined whether a second word that occurred at the same location or associated with the same moving object was detected more rapidly. They found a priming effect for same-location and same-object but little or no priming for items that had similar physical features or similar meanings (as indicated by common semantic features or similar category membership). From this they concluded that object files contained “abstract identity information,” but no physical form nor semantic information about the object. This is precisely what I have been claiming about bare indexes, although in other contexts, other kind of information may be stored in memory and associated with indexed objects. The priming methodology, it seems, was able to isolate the object-based information stored when the task did not require other information to be stored about the indexed objects.

Notice a certain similarity in the motivation behind this visual index assumption and the assumption that various “natural constraints” operate in early vision (as discussed section 3.1.1). In the cases where we appealed to the operation of natural constraints we were able to give a non-inferential account of certain phenomena of visual interpretation (such as the perception of structure from motion) that might appear to require inference from world knowledge. In these cases we found that on closer examination the phenomena could be explained more simply by assuming that the visual system had become wired (presumably through evolution) in such a way that, even though it was unable to use relevant knowledge of a particular scene, its operation was restricted in certain ways that ensured that representations of 3D layouts it computed was generally veridical in our sort of world. Similarly in the present case we hypothesize a tracking mechanism that appears to maintain individual identity – a task that in general *would* require appeal to concepts, descriptions, and inference – yet it does so without involving the conceptual system. As in the case of the natural constraints examples, this task is accomplished by what one might call an evolutionary heuristic: We have evolved a basic mechanism whose function, within its domain of application (or its “ecological niche”), is close enough to that of identity-maintenance that it can serve as a surrogate for full individuation and identity-maintenance. Such a mechanism maintains the correct identity-

correspondences in most circumstances of importance to us, in situations that are typical in our kind of world.

What this means is that in our theory neither *picking out* nor *tracking* are based on top-down *conceptual* descriptions, but are given pre-conceptually by the early visual system, and in particular by the FINST indexing mechanism. Moreover, the visual system treats the object so picked-out as distinct from other individuals, independent of what properties this object might have. If two different objects are individuated in this way they remain distinct as far as the visual system is concerned. They remain distinct despite certain changes in their properties, particularly changes in their location. Yet the visual system need not know (i.e., need not have detected or encoded) any of their properties in order to implicitly treat them as though they were distinct and enduring visual tokens. The theoretical claim is that in order to bind an object *x*, in this primitive sensory sense, there need not be any concept, description or sortal that picks out each token instance of an *x* by type. The individuals picked out in this way by the early visual system (by a mechanism described in table 1 and illustrated in Figure 5-4) are what I am referring to here as *primitive visual objects*. I use this technical terminology to distinguish these primitive visual objects from the more general sense of object, which might include invisible things, abstract things (like ideas) and other more usual notions of object, such as tables and chairs and people. This sense of object, as philosophers like (Hirsch, 1982; Wiggins, 1979) and others have argued, *does* require sortal concepts to establish criteria of identity. But our concern here will be with objects that are in the first instance defined in terms of the special sort of primitive nonconceptual category of objecthood induced by the early visual system. We don't know in any detail what properties define this sort of primitive objecthood, nor even whether it can be characterized in any way except in terms of the structure of our perceptual system. Thus, what we have so far is the claim that the early visual system must be able to individuate and keep track of certain primitively detected and primitively segregated visual objects over time.³⁶

The basic idea of the FINST indexing and binding mechanism is illustrated in Figure 5-4 below. A series of optically mediated events lead from certain kinds of primitive visual objects, via fundamental mechanisms of the visual system (including retinotopic grouping processes), to the establishment of a link with certain conceptual structures (which we may think of as symbol structures in Long Term Memory). This allows certain sorts of objects to *grab* or *seize* one of the small number of available indexes and thereby provides a means whereby certain conceptual entities (i.e., the active nodes or the items in working memory) can *refer* to these visible objects in the world. The important thing here is that the inward arrows are purely causal and are instantiated by the nonconceptual apparatus of early vision. This apparatus guarantees that under certain conditions of change (some of which will be discussed later), the primitive objects that caused the link will maintain it in unbroken continuity, thus resulting in its counting as the *same link*. By virtue of this causal connection, the conceptual system can *refer to* the primitive visible objects. It can, for example, interrogate them to determine some of their properties, it can evaluate visual predicates (such as *Collinear*) over them, it can move focal attention to them, and so on. The way in which this can be done is illustrated in Appendix 5A, though merely to show that nothing mysterious is being assumed here. It is a straightforward problem of how to use a causally established link to send signals back to the original cause.

³⁶ Confining this discussion to the visual system is an interim measure because the empirical data that we have so far are primarily concerned with the visual system. But it seems clear that this notion will have to be extended beyond vision to include other sense modalities. For example, there is considerable evidence that under certain circumstances we can pre-conceptually track distinct melodies embedded in other melodies or chords (Bregman, 1990) and that we can track the movement of several sound sources in a dark room. Although these are all relevant to the notion of individuation, tracking and indexing, an examination of non-visual phenomena is beyond the scope of the present essay.

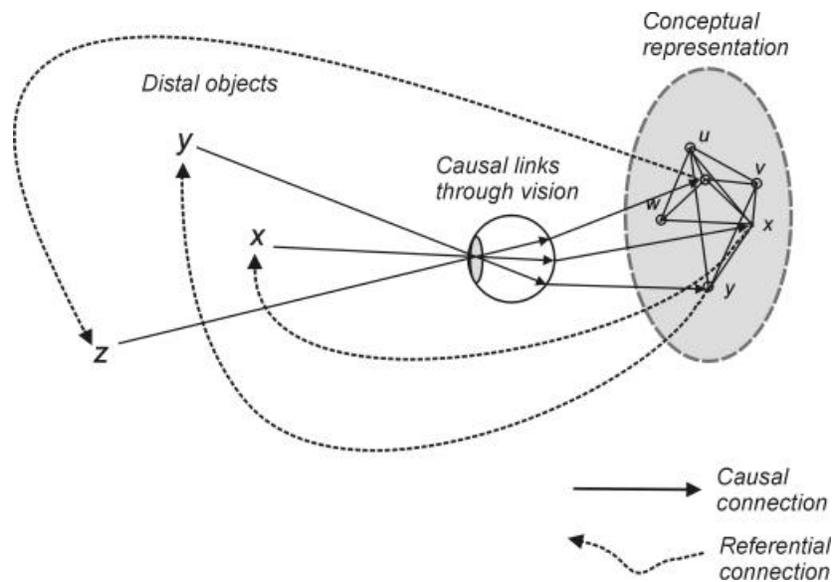


Figure 5-4: Sketch of the types of connections established by FINST indexes between primitive visual objects x , o , z and parts of conceptual (descriptive) structures.

Before I turn to a discussion of the empirical support for the indexing hypothesis, two points of possible misunderstanding need to be cleared up. First, the reader may have noticed that there is a systematic ambiguity in the above discussion, an ambiguity that I have deliberately left open. Sometime I refer to the cause of the index assignment – the primitive visual object – as being a *proximal object*, perhaps a projection on the retina, and sometimes (as in Figure 5-4) I have assumed it to be the *distal object* in the world. Of course both are involved since they are links in the same causal chain from distal object to mental index. But it matters a great deal whether the index is taken (by the cognitive system) as pointing to a proximal or a distal object. Here I must take a stand, for there is typically no interest in pointing to a proximal (e.g., retinal) cluster, although it is a logical possibility. The essential function of indexes is to pick out and refer to *distal* objects. It is only when elaborating on the nature of the links in the causal chain that we may need to go into detail about the steps that intervene between the distal object and the visual index. We do this when we give a theory of how indexes are implemented in the brain or in a computer, or perhaps when we wish to explain certain deviations of the mechanism's behavior from what I have alluded to as demonstrative reference. Of course when the objects being indexed are marks on a computer screen the situation remains ambiguous: The observer may be indexing clusters on the screen or, more likely, the observer is indexing a virtual distal object where only the part of the chain from the display to the observer is real. This is like asking what the observer sees when looking at a picture of a meadow; a pattern on a screen or a virtual or possible scene in the world. Although some ambiguity remains (since the observer likely sees the meadow as being pictured on a 2D surface and can decide to focus on the pixels or the pen strokes) the most accurate way to describe the situation is as the percept being of a (possible) 3d scene.

The *second* point of potential misunderstanding concerns what I mean when I claim that no concepts or encodings of properties of the objects are involved in assigning or in maintaining indexes. A reader might wonder how an index could be assigned – could be the outcome of a causal chain – if not in virtue of *some* property. My claim is not that no property is involved, but that no represented (or encoded) property is used in the assignment of an index. But does not *some* part of the nervous system encode the property that causes the index to be assigned (or that causes the index to remain bound to the object)? Not every causally efficacious property impinging on our nervous system results in a representation of that property. (Uttal, 1967) made a distinction between codes and signs for just this reason. Uttal points out that the nervous system, qua physical system, may react to certain forms of energy arriving at its surface, yet the reaction may nonetheless fail to *represent* anything, in the sense that the change in the system's state is not a computational one. Striking a computer may change some things (e.g., its appearance, its position, the

relative location of its parts – perhaps even the relative temperature of various parts) without the changes being computationally relevant. Even changing the keyboard may change the way the computer reacts to certain keystrokes, but not in the same way as it would if the program or the data were changed; the changes would be in a peripheral pre-computational stage. Similarly it may be that a sudden onset causes an index to be assigned without the assignment carrying the information that there was an onset; it is not encoded as an onset, and perhaps not encoded at all, just indexed. Part of the reason that the assignment of an index could fail to carry the information that a sudden onset had occurred is that on another occasion it may be that having a unique color or brightness causes the assignment of an index. So it could be that no *particular* property causes an index to be assigned, but very many different properties may have that cause on different occasions. It could be, for example, that anything that causes a sufficient activation in the early vision system is assigned an index, in which case the set of properties that invoke indexes may be highly disjoint and their only commonality might be that they cause a particular reaction in the early visual system. In that case we would say that it is a mechanism-dependent (or what philosophers call a “mind-dependent”) property. So once again the particular property that caused the assignment need not be encoded anywhere. The same thing is true of the claim that objects are indexed without appeal to their location. The objects are, of course, at *some* location, and have particular properties, and perhaps if that were not the case they would not be indexed or the index could not be used to move focal attention to the indexed object. Perhaps also if it did not change location in certain ways one could not track it. So location appears *prima facie* to be an important property for assigning and maintaining indexes. But that does not mean that a property like location is encoded, or that indexing or tracking is carried out by means of detecting locations or trajectories.

But this leaves an apparent puzzle: How can a person or a robot carry out an action like pointing to, moving attention to a particular individual object, as I claimed in item (8) of Table 5-1 unless it knows *where* the object is located? This apparent puzzle rests on a misleading way in which the question is asked since it assumes a particular frame of reference or a particular way of specifying the target object. All you need is an unambiguous way of picking out or indexing the object in question and then a way of using this index in a motor command, nothing more. As for the first requirement (indexing), there is no reason why you cannot uniquely specify the target of an action without specifying the location (or any other property) of the target. For example, (Ballard et al., 1997) have shown that a particularly efficient way of indicating (or referring to) the target of an intended action is by a deictic reference; namely by looking (or directing one’s gaze) at it. As for the second requirement (the motor command), once you have uniquely specified a target there is no reason why you could not design a robot so that MOVE(x) could be executed without there being any explicit representation of *where* x is, so long as x bound to the target object. For example, you can specify that the action be directed to the object of the gaze, or in the direction of the line of sight. Notice that “the object I am looking at” does not pick out an individual object by its location, since its location is nowhere specified.

The question of how you could build a robot to carry out such a command is an implementation question. However the visual control of a robot is implemented, the appropriate characterization of the way the visual system controls movement might be to say that MOVE(x) is a primitive command that can be executed if x is bound to an object in the visual field, and that the question of exactly how it is executed lies outside the level of abstractness (or what Newell & Simon, 1972, call the “level of aggregation”) that the theory addresses. This is, after all, what we say about all primitive information processing operations that are part of the architecture of the system. It is what we do say, for example, for primitive operation such as store, retrieve, match, and so on.

There may be good reasons why you might use magnitudes such as distance, direction, time, etc as the basis of implementing ways of executing the MOVE(x) command. But you need not. One can easily imagine a system that does not control a robot by means of measurements and computations over location parameters. For example, a robot that was simply told to move to the object in its gaze could just continue moving in a way that keeps its gaze centered on the target, without ever “knowing” *where* the target was in terms of some allocentric frame of reference (nor, for that matter, need it know any properties of the target except that it was in its cross-hairs). It could do so because of the causal (not computational) structure of the connections between head position and wheels and the head position could be controlled by a simple

feedback mechanism such as occurs in a feedback-based servomechanism. In such a mechanism one often controls a property that is not directly measured or encoded, simply by relying on some easily detected correlates of the property. For example in order to catch a fly ball, a baseball fielder apparently moves in such a way as to nullify the apparent curvature of the ball's flight, so it looks like it is descending in a continuous straight line (McBeath, Shaffer & Kaiser, 1995). Thus the property that the player wishes to control (the player's location at the time the ball is about to hit the ground) is nowhere represented, nor is any other magnitude of the ball's motion except the deviation of the ball's trajectory from a straight path. Another example is the autofocus feature of many cameras. Autofocus does the equivalent of setting the focus ring on the camera to the appropriate distance. But none of the autofocus mechanisms actually *measure* distance directly, and consequently no distance measure is ever encoded. What the mechanisms measure may be time delay (sonar method), angle (triangulation method), intensity (infra-red method), spatial spectrum (contrast method), or phase difference between two sensors (phase matching method). The measured quantities enter into physical relations with the motor system; but neither the measured quantities nor the implied distance are available outside the control system. Although the function that is computed may be properly characterized in terms of distance between camera and subject, the relevant distance parameter nowhere enters the process. Consequently there should be nothing surprising about the claim that in order to move towards (or point to) an object no location encoding is required, only a way of individuating and indexing the object, along with relevant motor commands to whose arguments such an index can be bound. All else is implementational detail with many possible instantiations. (For more on the relevance of deictic pointers to robot control, see section 5.3.2)

The idea of a deictic reference can be made quite concrete in terms of the mechanism of a visual indexing and the experimental phenomena to which they have been applied. For this reason I now turn to the elucidation of the idea of a visual index by describing a number of experiments we have performed over the past 15 or so years motivated by this theory. These studies (many of which are summarized in Pylyshyn, 1998, 2001a, 2001b; Pylyshyn, Burkell, Fisher, Sears, Schmidt, & Trick, 1994) provide a wide range of support for the basic ideas introduced above and have the further virtue of making the nature of the indexing claim concrete and operational.

5.2 Empirical Support for Visual Index Theory

5.2.1 The multiple object tracking (MOT) task

Perhaps the clearest way to see what it being claimed in the above discussion is to consider the first set of experiments to which these theoretical ideas were applied. The task involved is called the Multiple Object Tracking task and helps to make clear what is at issue. For this reason I will not only describe the basic experiments, but will also spend some time discussing what they mean in terms of plausible psychological mechanisms.

In a typical experiment (illustrated in Figure 5-5), subjects are shown a screen containing 8-16 simple identical figures or objects (e.g., points, circles, squares, plus-signs, figure 'eights'), which move in unpredictable ways, sometimes without colliding (because of a simulated barrier or "force field" between them) and sometimes (in more recent studies) allowing collisions and self-occlusions. At the start of each trial, a subset of these objects is briefly rendered visually distinct (usually by flashing them on and off a few times). The subject's task is to keep track of this subset of objects. At some later time in the tracking trial (say 5 to 10 seconds into the trial) all the objects stop moving and the subject has to indicate (using a mouse pointing device) which objects were the targets. A large number of experiments (beginning with studies by [Pylyshyn, 1988 #455]) have shown clearly that subjects can indeed track up to 5 independently moving identical objects (i.e., objects that are indistinguishable by any property other than their historical continuity with the initially distinct objects). The question to be answered is: How do people do it?

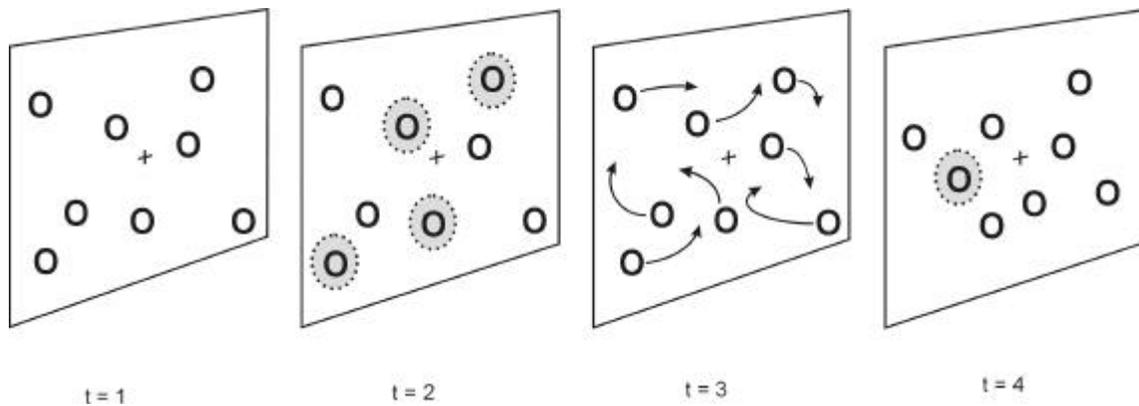


Figure 5-5. Illustration of a typical Multiple Object Tracking experiment. A display of eight identical objects is shown ($t=1$) and a subset of 4 are briefly flashed to make them distinctive ($t=2$). Following this ($t=3$) the objects stop flashing, so the “target” set is indistinguishable from the other objects. All objects then move in a random fashion for about 10 seconds. Then the motion stops ($t=4$) and one of the objects is flashed. The observer’s task is to say whether the flashed object was one of the objects that had been initially flashed (in this case the answer is yes). In other experiments the observer has to indicate all the tracked objects by clicking on each one using a mouse.

If there had only been one object to track the answer would be relatively easy: Observers could simply track it with their eyes, or perhaps they could track the moving object using attention scanning (such error-driven tracking systems have been common since the development of feedback control theory and servo-mechanisms). But how do observers do this task with 4 objects moving along independent random trajectories interspersed among 4 other identical “distractor” objects that must be ignored. One possibility is that observers record and use the locations of each target object and visit them serially. After the initial recording of target locations they simply go to the location in the list that they have stored and look around for the nearest object, taking that to be the target they are tracking and updating its location code in the list using the following algorithm:

1. While the targets are visually distinct, scan attention to each target and encode its location on a list. Then, when targets begin to move;
2. For $n=1$ to 4; Check the n 'th position in the list and retrieve the location $Loc(n)$ listed there.
3. Scan attention to location $Loc(n)$. Find the closest object to $Loc(n)$.
4. Update the n 'th position on the list with the actual location of the object found in #3. This becomes the new value of $Loc(n)$.
5. Move attention to the location encoded in the next list position, $Loc(n+1)$.
6. Repeat from #2 until elements stop moving.
7. Go to each $Loc(n)$ in turn and report elements located there.

So long as attention can move fast enough from one object to another, and the objects themselves are not moving too fast in relation to the speed of scanning attention, and the nontargets are sufficiently far from the targets to prevent frequent mistakes, such a strategy of serial attending and recording of locations might explain the better than chance performance. In (Pylyshyn & Storm, 1988), however, we were able to show that the motion and dispersion parameters of our original experiments were such that tracking could not have been accomplished using such a serial strategy. The performance of the above algorithm when it is applied to the actual displays used in the Pylyshyn & Storm study results in the performance shown in Figure 5-6 below.

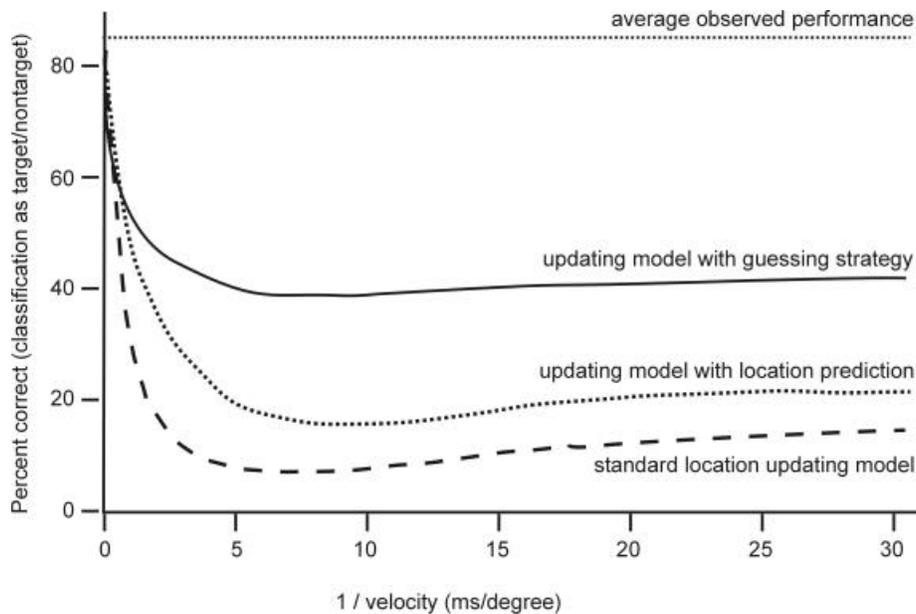


Figure 5-6. Performance of the scanning and location-updating algorithm given above, at various scanning speeds, when applied to the actual experimental displays described in (Pylyshyn & Storm, 1988).

Based on the assumption that in order to encode location, focal attention must be allocated to the object, we were able to simulate the serial strategy on the actual trajectories used in the experiments, for various attention-scanning speeds (assuming zero dwell time at each object). The simulation showed that such a serial tracking strategy would very frequently end up switching to tracking nontargets in the course a trial. Indeed even if we assume the fastest attention-scanning speed ever reported (4 ms/degree), this strategy could not perform better than about 20% correct in tracking the targets (this estimate can be increased to just under 50% if we allow for a guessing strategy). The observed human tracking performance, by contrast, was about 88% correct on average. We have now replicated this result in dozens of different experiments and found that performance in tracking 4 objects in a field of 8 rarely falls below about 85% and for some people remains over 95%. Indeed, many college subjects have no difficulty in tracking five objects.

What this means is that in the multiple object tracking studies, observers could not have been keeping track of the targets by using a unique stored description of each object, since at each instant in time the *only* property that is unique to each object is its location. If I am correct in arguing from the nature of the tracking parameters that stored locations cannot be used as the basis for tracking, then all that is left is the object's *individuality*. The individuality of the target objects is initially established by making them distinct (by flashing them). From then on it is the historical continuity that determines their identity – where the operative phrase “historical continuity” is defined strictly in terms of the hypothesized primitive mechanism for individuating and tracking: the visual index (or FINST). It is this mechanism that defines a primitive perceptual individuality that persists over time (at least for times as short as 10 seconds and with motion parameters within the range explored in our studies).

The multiple object tracking task exemplifies what I mean by “tracking” and by “maintaining the identity” of objects. It also begins to define what is meant by a primitive visual object³⁷ – it is whatever attracts and maintains indexes for the purpose of tracking. The task also operationalizes the primitive notion

³⁷ It is somewhat awkward to keep having to say “primitive visual object” to refer to objects as defined by indexing theory. I have occasionally been tempted to call things picked out by FINSTs as FINGs. Now and then I may succumb to this temptation in order to emphasize the mechanism-relativity of this notion of thing or object.

of “same object” – an object is the “same” if it continues to be bound to the same index despite changes in the object’s location and other visual properties. That is how the early visual system picks out some primitive individual object P, rather than taking them to be, say, a sequence of time slices P_1, P_2, \dots, P_t . If the latter were the way that the visual system parsed the world then it would need to re-recognize each of the individual P_i s in some way (say by virtue of their sharing certain properties) in order that they might be viewed as constituting the same individual P. Most re-identifications are doubtlessly of this kind. In order to know that the person I saw in a certain movie is the same person whose picture is on my wall and the same person I saw in the store today I must surely carry out a complex process of describing and comparing descriptions. What I am claiming here is that there are certain primitive cases of identity-maintenance that do not require such a conceptual-descriptive apparatus.

5.2.2 Other properties of visual indexing revealed through MOT

Over the past decade, a large number of additional experiments in our laboratory (McKeever, 1991; Scholl & Pylyshyn, 1999; Sears & Pylyshyn, 2000) and elsewhere (Cavanagh, 1999; He et al., 1997; Ogawa & Yagi, 2002; Slemmer & Johson, 2002; Suganuma & Yokosawa, 2002; Yantis, 1992) have replicated these multiple object tracking results, confirming that people can successfully track several independently moving objects. Some of these studies carefully controlled for guessing strategies and also demonstrated patterns of performance that are qualitatively different from those that would be predicted by any reasonable serial-scanning algorithms we have considered (see Pylyshyn et al., 1994). The results also showed that a zoom-lens model of attention spreading (Eriksen & St. James, 1986) would not account for the data. Performance in detecting changes to elements located inside the convex hull outline of the set of targets was no better than performance on elements outside this region, as would be expected if the area of attention were simply widened or shaped to conform to an appropriate outline (Sears & Pylyshyn, 2000). (Intriligator & Cavanagh, 1992) also failed to find any evidence of a “spread of attention” to regions between targets in their research, using a different tracking methodology.

The sort of “pre-conceptual” tracking explored in these studies has turned out to have some surprising properties. For example, (Scholl & Pylyshyn, 1999) showed that tracking can be disrupted by objects disappearing for a few hundred milliseconds and then reappearing, whether or not the disappearance and reappearance is abrupt or gradual (e.g., if they shrink into a point and expand from a point). But if the objects disappear and reappear in a manner consistent with their going behind an occluding surface, tracking is not significantly disrupted – even if the edge of the occluding surface is invisible (i.e., it is a “virtual occluding surface”). This is true even if the occluding surfaces are not global, so that different objects go behind different virtual occluding surfaces. All that is required is that the objects are seen as disappearing by having their leading edge accrete as they move behind the occluding surface and then emerge again as though reappearing at a disoccluding edge. (Viswanathan & Mingolla, submitted) also showed that objects can even occlude one another in their travels, providing there are local cues (e.g. T-junctions) that one is in front of the other. Because of this, later versions of multiple-object tracking experiments have primarily used open circles and have allowed objects free-reign in their trajectories.

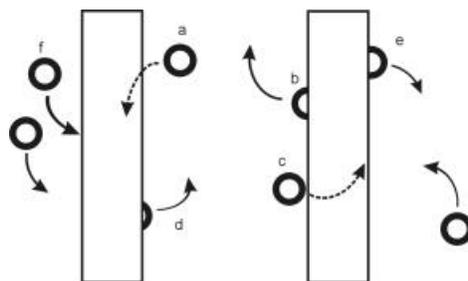


Figure 5-7. Objects can be tracked despite their brief disappearance behind occluding surface and despite self-occlusions when their shapes provide clues (T-junctions) as to which one is in front (as in the case of the rings shown here).

Among the studies we have carried out over the past decade is a set of experiments that explored the question of whether indexes could be assigned voluntarily, or whether only automatic data-driven events could cause indexes to be assigned (Annan & Pylyshyn, 2002). The results were somewhat surprising; they suggested that indexes could be voluntarily assigned but only if sufficient time is available. We interpreted this result to mean that while voluntary assignment of indexes was possible, the indexes had to be assigned by serially visiting the objects to be indexed and allowing the assignment to take place (one might say that one could visit objects and “drop off” indexes on the way). If we used straightforward methods of specifying which objects were to be tracked (e.g., numbering them 1 through 8 and telling the subject to track objects numbered from 1-4) then, not surprisingly, subjects could do this only if sufficient time was allowed and failed if the time available was too brief to allow the numbers to be scanned serially (it is, after all, hardly surprising that the numbers had to be serially read before they could be tracked). But we also introduced a variety of novel procedures for specifying which objects were to be indexed and tracked. Each of these provided information that segregated the set of objects quickly, and then we varied the time available to pick one half of the segregated set for tracking. Here is an example of this technique. When 4 of the 8 objects are flashed on and off either very briefly (one off cycle of 180 ms) or for a longer time (three off-on cycles totaling 1020 ms) the flashed objects could be easily tracked in either condition. But when instructed to track the objects that had *not* been flashed, subjects could only do so in the long-flashing condition; they could not track the clearly segregated set if they did not have sufficient time to visit the non-flashed objects.

We also explored the question of what sorts of visual clusters qualify as “objects” in our sense. We have not explored this question in depth, but we already have some interesting findings (Scholl, Pylyshyn & Feldman, 2001). We have shown that not every well-defined cluster of proximal stimulation can be tracked. In particular, it appears that certain easily defined *parts* of objects cannot be tracked. Figure 5-8 shows an example in which we connected pairs of objects that could easily be tracked. The connections were drawn in various ways, from simple connecting lines, to complex connections of various kinds. Some of these lines created perceptually salient and stable new objects while others created more tenuous new objects. When the connections created salient new objects by merging the original objects, the original objects could not easily be tracked. For example, the endpoints of lines could not be tracked, even though their trajectories were identical to those of dots that were easily tracked. The question of whether the poorer tracking was attributable to the formation of strange elastic objects was addressed recently by (Suganuma & Yokosawa, 2002), who showed that even if the merged objects maintained individual rigid shapes in 3D when viewed stereoscopically, target merging strongly compromised observers’ ability to track the individual targets that were merged in this way.

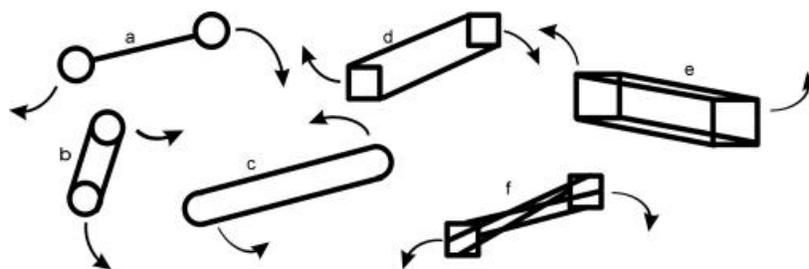


Figure 5-8. Examples of displays in which a target object is paired with a nontarget object by drawing various forms of connections between them. Objects which had been easy to track by themselves now become difficult when they are seen to be parts of other objects. In this set, (c) and (e) are very difficult, whereas (a) and (f) are easier because the parts that have to be tracked are not as integrated into the new objects (despite the fact that figure f involves as many connecting lines between the two squares as does figure e).

A few of the results we have obtained do seem at first glance to run against the basic assumptions of index theory. One of these will be described to show the sort of methodologies that have been used to

investigate this process. We kept finding that as the number of non-target objects was increased there was a decrement in performance, contrary to the prediction from pure indexing theory (nothing about the nontargets should influence tracking of targets since the tracking is supposed to be determined solely by the index mechanism that was being driven by the movement of the targets). Chris Sears and I (Sears & Pylyshyn, 2000) reasoned, however, that this performance decrement might have occurred because as the number of nontargets increased, the chance of mistaking a nontarget for a target and switching to tracking the nontarget would increase. We then devised a method for showing that this was indeed the case. Subjects had to track a number of target figures that moved among a larger set of nontargets. All objects (both targets and non-targets) were shaped like a square “8” () and some time during the trial one of the objects changed into either an E or an H. Subjects then had to make a dual response: they had to press one of a pair of buttons indicating that an object had changed into either an E or an H, and they also had to indicate separately whether this change had occurred on a target or a non-target. As usual, performance on detecting a change on targets decreased when the number of nontargets increased. But since we had a measure of how often subjects mistook a non-target for a target, we were able to confirm that the number of switch-over errors increased as the number of non-targets increased, just as we had surmised. Moreover, when we analyzed performance on the objects that subjects *said* were targets (whether or not they actually were) performance was *not* affected by changes in the number of non-targets. In other words, if we take into account the increased frequency of erroneously switching to a nearby non-target, a type of error that went along with there being more non-targets in the display, then tracking was unaffected by the number of non-targets around.

From these MOT studies it appears that objects can be tracked despite the lack of distinctive properties (and, indeed even when their properties are continuously changing) and despite unpredictable motions and constantly changing locations. The empirical case for indexing theory, however, does not rest solely on the multiple object tracking procedure. I offer several other experimental demonstrations that support the existence of such a mechanism.

5.2.3 Selecting objects in a search task

Another illustration of what is meant by an index is provided by a series of studies we have performed involved the selection of objects in a visual search task. The search task we used was adapted from one originally introduced by (Treisman & Gelade, 1980). In the original studies (described briefly in Chapter 4) Treisman and her colleagues asked subjects to search for a certain specified (unique) target within an array of non-target or “distractor” objects. The target in many of these studies (as well as in our variant) was a simple item (such as a short line segment) with several distinctive properties, such as its orientation (/ or \) and color (red or green). Of particular interest was the comparison between two conditions. In one condition, called single-feature search, the target differed from all distractors in one particular distinguishing property; for example, the target might be the only red object in the display. In another condition, the target differed from the distractors in having a unique combination of two or more different kinds of properties. For example, in this condition some distractors had the same color (but different orientation) while others had the same orientation (but different color), so that the target was defined only by the combination of a certain color with a certain orientation (e.g., it was the only green, right-oblique line segment among red right-oblique and green left-oblique segments). This second condition was called a conjunction-feature search, and proved to be a great deal more difficult. Treisman and her colleagues found that in the single-feature condition, the search slope was very low – i.e., the search time increased very little with increasing numbers of distractors. This led Treisman & Gelade (and many others after them) to refer to the single-feature condition as a “popout”, suggesting that the target “pops out” to the observer, rather than having to be searched for. In the conjunction-feature condition, by contrast, each additional item that was added to the array substantially increased the time it took to find the target. This was interpreted as indicating that unique single properties could be detected by a parallel process whereas pairs of properties had to be searched for serially, item by item. Although the serial-versus-parallel distinction has been subject to a great deal of criticism in recent years, the basic finding that detecting single-property objects shows a different pattern of search than detecting conjunction-property items remains an important finding, for which various

theories have been proposed (see, e.g., Pashler, 1995). From our point of view, the details of the manner in which target items are recognized is not what matters. Rather we are concerned with the way in which the visual system locates items in order to determine their properties. And here we have made use of the interesting difference between searching for single-feature targets in contrast to searching for conjunction-feature targets.

In our studies we have used both single-feature and conjunction-feature searches under conditions in which we provided subjects with a way to select a certain subset of items and essentially ignore the items that would ordinarily slow down the search. Visual indexing theory claims that indexed objects can be accessed directly through the indexes. Consequently if a subset of objects was indexed, observers could confine their search to that subset of objects and ignore the rest. The interpretation of these studies in terms of indexes rests on one additional independently verified assumption – that the sudden onset of a primitive object in the visual field elicits indexes. In a series of studies, Jacquie Burkell and I (Burkell & Pylyshyn, 1997), showed that sudden-onset location cues could be used to control search so that only the precued locations are visited in the course of the search. This is what we would expect if the onset of such cues draws indexes and indexes can be used to determine where to direct focal attention. In these studies (illustrated in Figure 5-9) a number of placeholders (11 in the case illustrated), consisting of X's, appeared on the screen and remained there for some period of time (at least one second). Then an additional 3-5 placeholders (which we refer to as the “late-onset cues”) were displayed. After 100 ms one of the segments of each X disappeared and the remaining segment changed color, producing a display of right-oblique and left-oblique lines in either green or red. The entire display had exemplars of all four combinations of color and orientation, so that the search was technically always a conjunction-search task. The subject's task was to report whether the display contained a pre-specified item type (say a right-oblique green line). As expected, the target was detected more rapidly when it had been precued by a late-onset cue, suggesting that subjects could directly access those items and ignore the rest. There were, however, two additional findings that are even more relevant to the indexing theory. These depend on the fact that we manipulated the nature of the precued subset to be either a single-feature or a conjunction-feature search.

As mentioned above, a search of the entire display in these studies would always constitute a conjunction-feature search. However, the subset that was precued by late onset cues could be either a simple or a conjunction-feature subset. So the critical question is whether the property of the entire display or the property of only the *subset* determines the observed search behavior. We found clear evidence that only the property of the subset (whether it constituted a simple-search or a conjunction-search task) determined the relation between number of search items and reaction time. This provides strong evidence that only the cued subset is being selected as the search set. Notice that the distinction between a single-feature and a conjunction-feature search is a distinction that depends on the entire search set, so it must be the case that the entire precued subset is being treated as the search set; the subset effect could not be the result of the items in the subset being visited or in some way processed one by one.

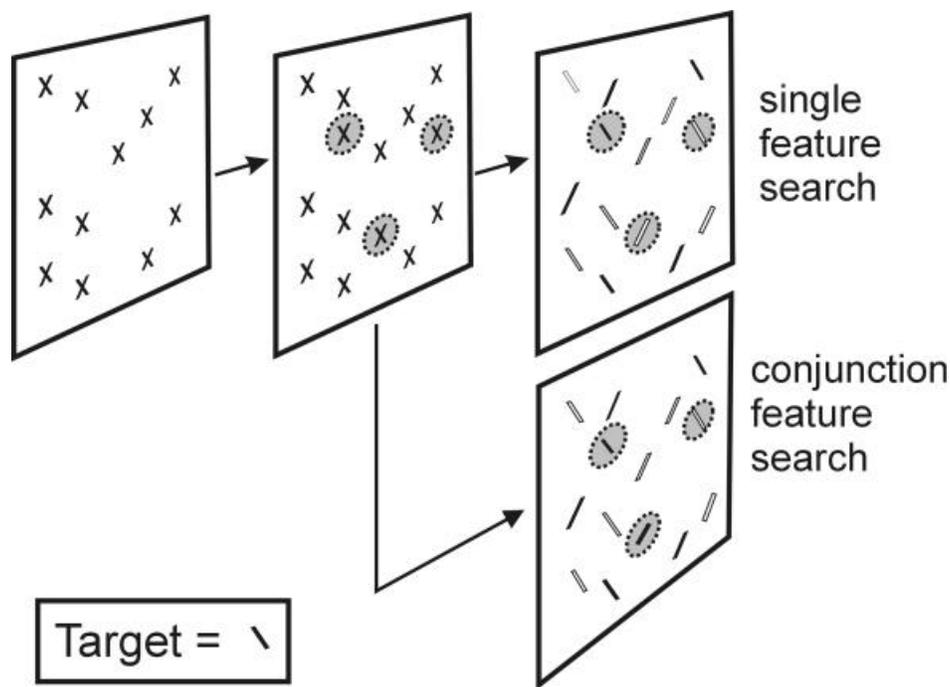


Figure 5-9: Sequence of events in the (Burkell & Pylyshyn, 1997) study. In the first frame the observer sees a set of placeholder X's for 500 ms. In the second frame, "late onset" placeholders appear for 100 ms, signaling the items that will constitute the search subset. In the last frame all placeholders change to search items and the subject must try to find the specified target in one of the two conditions. In the top display the target differs from the nontargets by one feature whereas in the bottom display on the right only a combination of two features distinguishes the target. Note that the entire display contains all four types of items, so that relative to the entire display this would be a conjunction-feature search task. (The faint circles do not appear in the display – they are only for expository purposes).

Of particular relevance to the indexing thesis was the additional finding in the Burkell & Pylyshyn study that when we systematically increased the distance between precued items there was *no* increase in search time per item, contrary to what one would expect if subset items were being searched for. It seems that the spatial dispersion of the items does not affect the time it takes to examine them, even when the examination appears to be serial (e.g., the time increases linearly as the number of nontargets increases). This is precisely what one would expect if the cued items were indexed and indexes are used to access the items without spatial scanning.

The basic subset result has recently been replicated using the Multiple-Object tracking method to establish indexes, instead of the late-onset method. When all objects in an MOT experiment change into search items and the subject is required to search only among the tracked objects, the same results are found as were found in the (Burkell & Pylyshyn, 1997) study. Such studies provide a clear picture of one of the properties of indexes that has not been emphasized in the earlier discussion: Indexes provide a *direct access mechanism*, rather like the random access mechanism found in all modern computers. Once certain elements or primitive visual objects have been indexed, one can make inquiries of them. For each indexed item one can ask whether it is "red" or "slanted to the right" and so on. Moreover, accessing the items for this purpose does not involve searching the display for a certain property – one can direct an inquiry concerning a certain visual property specifically at a particular item by using the index the way one uses a variable or a pointer in a computer data structure. One can ask "Is item x red?" so long as x is bound to some primitive visual object. Moreover, it appears that one can ask it directly of object x without first searching for an object of a certain type. In other words, one need not search for a target by finding at object having a certain orientation property and then asking whether it has a certain color using a form of question such as, "Is the item that fits the description 'is slanted left and located two-thirds of the way

between the fixation cross and the left edge of the screen' colored red?" But this is precisely the sort of process one would have to go through if one could not specify which item one had just found (i.e., one with a particular orientation) except by using a unique description of it.

5.2.4 Inhibition of return

In Chapter 4 (section 4.5.3) I described the phenomenon referred to as Inhibition-of-Return (IOR), wherein it takes longer for attention to return to an object that had been attended some 500 ms to 900 ms earlier (Klein, 2000). This phenomenon, we saw, was largely object-based – in other words it was not primarily the previously-attended location to which attention was slow to return, but to the particular previously-attended object, which might have moved in the meantime (though location does appear to be relevant as well Tipper et al., 1994). But it is also the case that IOR appears to operate simultaneously over several objects, suggesting that it is not the allocation of attention that results in IOR but something more like the indexing of objects. For example, (Wright & Richard, 1996) showed that as many as 4 objects can be inhibited at once. (Sears, 1996) also reported that several loci could be inhibited in an IOR situation and showed that, as in the Burkell et al findings discussed in the previous section, there was no effect due to the distance between these loci, suggesting that the effect is both multiple and punctate just the way that we argued was the case with visual indexes.

5.2.5 Subitizing

Other studies have shown the power of this framework to account for a large class of empirical phenomena in which simple primitive visual objects are rapidly and pre-attentively individuated. One of these is the phenomenon called *subitizing* (Jensen, Reese & Reese, 1950; Kaufman, Lord, Reese, & Volkman, 1949), whereby the numerosity (or cardinality) of sets of less than about 4 visual items can be ascertained rapidly, accurately, and effortlessly. This is a particularly interesting application of Indexing theory inasmuch as the determination of the numerosity of a set of items is often taken to be the most elementary signature of what I have been calling *individuation*. It has long been known that enumerating sets of 4 or fewer items takes about 60 ms per item (we call this the *subitizing slope*). Above this number the enumeration rate goes up to 100-200 ms per item (we call this the *counting slope*) (see note 30 for how we determined where the slope changed). The question of why the slopes should be so different has been the subject of speculation and various alternative explanations have been offered (see the review in Trick & Pylyshyn, 1994b). Subitizing clearly involves both individuating items and enumerating them in some way in order to deciding their numerosity. Deciding the numerosity of the set of items appears to be a serial process involving visiting each item. But what about the individuation stage? It was shown by (Sagi & Julesz, 1984) that the shallow subitizing slope of about 60 ms per item is itself not due to the process of individuating items but to the subsequent enumeration process. They demonstrated this by showing that the slope is essentially zero when the task is to judge which of two displays (of size 2 vs. 3 or 3 vs. 4 items) is more numerous. This is not true outside the subitizing range, where the numerosity of the set does matter a great deal. But if the slope is due to the “counting” process, why is the slope so much larger for sets of more than 4 items? Our surmise was that in the small (subitizing) sets, the items are individuated pre-attentively and in parallel by the indexing mechanism. The enumeration can then be achieved by merely counting active indexes, without scanning and searching for the indexed items and enumerating them in the process. But if there are more than 4 or so items in the display, they cannot all be indexed so they must be located one at a time and their number determined by a process of scanning and counting (or perhaps, as Mandler & Shebo, 1982, have suggested, they might be segregated into smaller indexable groups, and then subitized and the results added). Thus we hypothesized that indexes play the decisive role in enumerating items in the subitizing range. Our analysis of the data has yielded strong evidence for this view. The following two findings are particularly relevant.

(1) *Subitizing does not occur when pre-attentive individuation is prevented.* We have shown that when feature clusters are not automatically individuated and indexed by the early visual system, no subitizing occurs (Trick & Pylyshyn, 1993; Trick & Pylyshyn, 1994a, 1994b). If, for example, targets are defined by conjunctions of features (which we have seen means that to identify them one has to focus

attention on them one at a time), there is no special subitizing slope – the enumeration slope is continuous (and high) throughout the range of numerosities. Similarly if items to be enumerated are defined by a property known to require focal attention for its detection, then no subitizing is observed. One example of this, discussed in Chapter 4, is the enumeration of figures that are arranged concentrically (as opposed to located side-by-side). Concentric squares (illustrated in Figure 4-5 and Figure 5-10) cannot be subitized, presumably because we cannot individuate them as individual whole figures without tracing their boundaries.

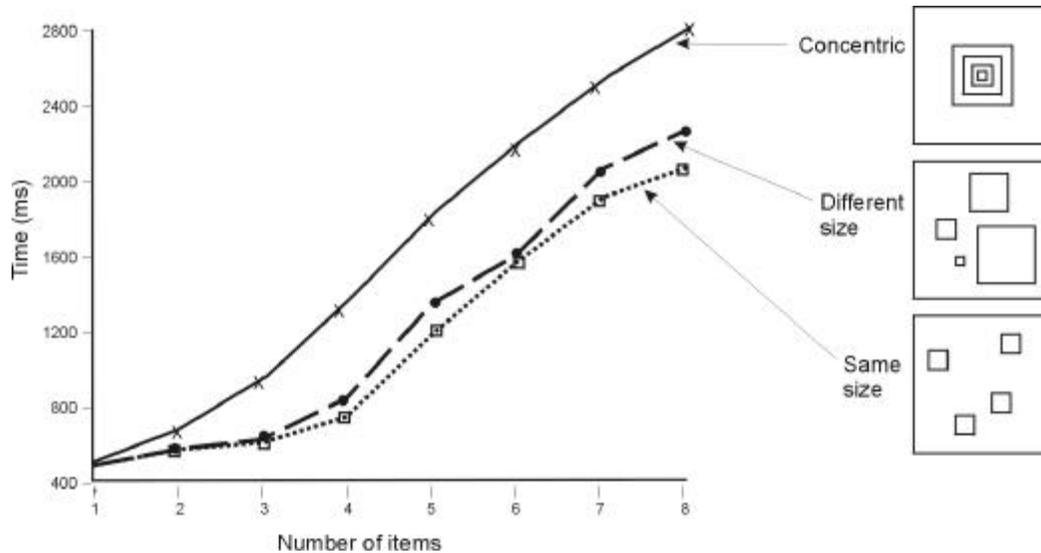


Figure 5-10. Graph of reaction time versus number of items enumerated, for several conditions examined in (Trick & Pylyshyn, 1993). Concentric squares do not show the characteristic “knee” in the curve that is the signature of subitizing.

Another related condition that we examined is the task of enumerate all items lying on a particular contour (as shown in Figure 5-11). This condition does not allow subitizing since evaluating the property “on the same contour” requires serial scanning (as Jolicoeur, 1983, showed). Similarly, subitizing does not occur when items appear gradually (Wright & Richard, 1995), presumably because the gradual appearance of objects does not capture visual indexes.

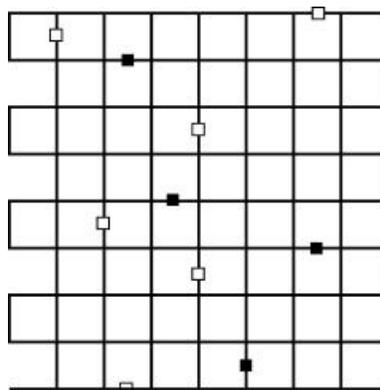


Figure 5-11. Example of a display in which observers had to enumerate either all black dots or all dots lying on the same contour. Only the former exhibited subitizing (based on Trick & Pylyshyn, 1993)

(2) *The spatial layout of a display is irrelevant in subitizing.* We have shown that the varying the spatial distribution of objects in a display or even precuing the locations of objects (with either valid or invalid location cues) is relatively unimportant in the subitizing range but critical in the counting ($n > 4$) range

(Trick & Pylyshyn, 1994b). These findings are consistent with visual indexing theory which claims that the cardinality of the indexed subset can be determined by counting the objects that were indexed *without* having to spatially scan focal attention over the display (since indexes makes it possible for objects to be accessed directly without search), or even by just counting the number of active indexes. In either case, indexing eliminates the need to search a display for the items to be enumerated and therefore renders location cuing or using patterned displays less relevant.

These studies show that a preattentive stage of item individuation is critical for subitizing. Such a stage is postulated for entirely independent reasons by the present theory. (Simon & Vaishnavi, 1996) have argued that it is this individuation stage that is responsible for the limitation in the number of objects that can be subitized. Using an afterimage display they showed that even when indefinite time is available for counting, the subitizing limit remains. They take this as supporting the contention that it is not the task of counting that is the source of limitation, but the ability to individuate items.³⁸

Note that *counting* has been used as a paradigm example of why concepts are needed in order to pick out individuals. In order to count things, one must first specify what *sorts of things* are to count as separate and distinct things. So, for example, one cannot say how *many* there are in the room without stipulating conceptual categories by using terms, called *sortals*, such as “furniture”, “lamps” “people” and so on, that specify countable things (as opposed, say, to things that are also designated by nouns like water, air, wind, talk, or by adjectives like green or big). How is it possible then, to count or subitize without the top-down involvement of the conceptual system? If our interpretation of the subitizing studies is correct, it suggests that it is possible to count active indexes without specifying *what they index*. On the other hand this does presuppose that one intends to count indexes rather than thoughts or some other mental particulars. So at that level sortal concepts *are* involved in counting, just as descriptivist theories suppose. But the conceptual system is not involved earlier in specifying the individuals that elicited indexes. Of course in cases where one counts something other than primitively indexed objects, we *do* need a concept or sortal to pick out such individuals. For example, in the studies reported in (Trick & Pylyshyn, 1994b), there were conditions in which subjects were asked to count objects that had certain properties. In that case a conceptual selection is presupposed. In fact it is even presupposed in some of the popout cases, as when one is asked to count X's in a field of O's or red things in a field of green things. Counting and search may invariably involve a conceptual aspect in the way that tracking may not. When primitive visual objects are concerned, neither picking out the objects nor tracking them needs to involve a conceptualization, though the searching or counting stage very likely does.

In this section I have presented several types of empirical evidence supporting the view that there are mechanisms in early (pre-conceptual) vision that pick out individual objects in a primitive causal way; a way that depends only on the structure of the early visual system and not on what the organism knows or believes. We have also shown that this mechanisms (called a *visual index* or *FINST*) is capable of independently picking out several (around 4 or 5) such objects and of keeping track of them when they move around independently in unpredictable ways. There is more than can be said about the properties of this mechanism (and some of this has been presented in various publications e.g., Pylyshyn, 1998; Pylyshyn et al., 1994). The forgoing provides some of the basic empirically-motivated reasons for the postulated visual indexing mechanism, and thus supports our claims about the relation between mental representations derived from visual perception and the world we perceive. I now turn to the more general issue of why we need such a link.

³⁸ Some question has recently been raised as to whether the limit on the number of objects that could be enumerated in the (Simon & Vaishnavi, 1996) study might be due to the eccentricity of the targets being counted. (Intriligator, 1997) found that “attentional resolution” or the ability to individuate items (which is distinct from the ability to discriminate them) falls off with retinal eccentricity, suggesting that this in itself may account for the Simon and Vaishnavi finding. However this can't be the whole story since allowing eye movements in subitizing does not improve counting accuracy in general, except where it helps to group haphazardly arranged items (Kowler & Steinman, 1977). Moreover, even if the particular numerical limit reached in the Simon & Vaishnavi study resulted from loss of attentional resolution further from the fovea, it still remains true that the limit was indeed due to the *individuation* stage of the process since attentional resolution is measured in terms of the ability to individuate objects.

5.3 Why do we need a special connection between vision and the world?

The notion of a visual index, introduced in the last section in the context of certain phenomena of visual attention, has much broader implications beyond clarifying the nature of visual attention and showing the existence of a preattentive stage of item individuation and access. It helps us to understand how visual perception connects with *particular things in the world*. This may at first seem like a function already entailed by the very idea of vision, for after all is not vision itself what connects us with the perceived world? Of course this is true, but the usual kinds of theories of world-mind connection are incomplete and inadequate for many purposes. For example, the usual view of vision is that it is a process that provides a representation of the perceived world. We have already seen that there is some argument about the nature of this representation, and indeed, whether there is a single representation or many. Some feel that the early representation is picture-like, with the picture being laid out spatially, say in primary visual cortex. Marr's "primal sketch" is, in part, such a representation, though it is augmented with tags that provide symbolic information concerning the depth and orientation of surfaces, as well as information about how certain local features are grouped to form clusters. Others feel that the evidence favors the view that the output of the early visual system is a symbolic representation that is more language-like in that it uses a descriptive vocabulary of variable abstractness and, by the time it presents the information to the cognitive system, it no longer maps world space onto brain space (or some analogue surrogate) in the representational system. I discussed some of the arguments in Chapter 1 and I will have more to say about these issues in Chapter 7. Whatever the ultimate view of visual representation, however, there remains the question of how the system represents the fact that certain parts of its representation of a scene correspond to certain particular parts of the perceived world. If you take the descriptivist view you need a way to specify which particular token individual in the world corresponds to a particular symbol or expression in the description. If you take the pictorialist view, you need a way to specify which part of the mental picture corresponds to which part of the world. Even if the mapping were one-one and the mental picture preserved *all* the visible 3D details of the scene, which we know cannot be the case (see O'Regan, 1992; O'Regan, Deubel, Clark, & Rensink, 2000; Rensink, O'Regan & Clark, 1997; Simons, 1996), you need a way to specify that *this* bit of the representation corresponds to *that* bit of the world. Such a mapping of correspondences is essential if the visual process is to make connections among representations of objects in successive time intervals, successive glances across saccades, and successive elaborations of the representation over time. Such a correspondence matching is also necessary if vision is to make connections with the motor system to carry out such actions as move one's eye or one's hand in order to reach and grasp a particular individual (token) object.

What I call a "pure description" view has been the standard one in both artificial intelligence and cognitive science. A pure description is roughly one that uses only a structured arrangement of codes for properties and relations (technically, only predicates and variables bound by quantifiers) in describing a visual scene. Such representations pick out objects without regard for the context. For example, such representations might say such things as "There is a unique object that has properties P_1, P_2, P_3, \dots " or "The object that has properties $P_i \dots$ bears the relationship R to the object that has properties P_j " and so on. The important thing is that objects are picked out by definite descriptions (see note 39). (Or, as sometimes happens in computational models, objects may be referred to by *names* such as *Object-5*, as in Figure 5-13, where these quasi names are defined in terms of a description, so they function just as abbreviations for a unique descriptor, rather than true proper names that maintain designations in all possible contexts.) In particular, such purely descriptive representations do not use deictic terms such as "I" or "you" or "now" or "this" or "here," none of which can be understood (none of which succeeds in *referring* at all) without reference to the context of utterance.

Despite the widespread use of this type of purely descriptive representations, this form of representation will not do in general for a number of reasons. In what follows I will concentrate primarily on one empirical reason, based on the fact that visual representations must be built up over a series of glances or what might be called *noticings*, which leads to the problem of establishing correspondences between objects in different views. This correspondence problem is one of several reasons for the inadequacy of the "pure description"

view. Later I will briefly mention other reasons why the pure description view will not work, and I will introduce some more general arguments why we need to augment the types of referential terms used, to include visual indexes, which in many ways work like demonstrative terms such as “this” or “that.” This augmentation is needed in order to do the job required of visual representations, especially when they are used to guide actions.

Consider first the argument from incremental construction of visual representations. It is clear that visual representations are built up over time. There are many reasons for this, some of them empirical and some conceptual. For example, in section 3.3.1 I examined some empirical evidence for the articulation of the visual process over time. Also, as we saw in chapter 4, the capacity of the visual system is limited and this results in the necessity of allocating attention and consequently leads to a serial component in visual processing. (Tsotsos, 1988) has argued from a computational as well as neuroscience perspective, that the function of serial attention allocation is to ameliorate the computational complexity of vision. Indeed, (Ullman, 1984) has made a case that, even if there were no resource limitations in visual information processing, certain visual properties, by their very nature, could only be decided in a serial fashion using what he calls “visual routines”.

Another important reason why visual representations must be built up incrementally is the fact that the eye, through which all visual information must ultimately pass, has a highly limited spatial bound and requires frequent eye movements to build up a percept. In Chapter 1 we saw that a superposition explanation of this saccadic integration process runs seriously afoul of the empirical data. Yet anything else raises the question of how information from one glance is integrated with information for a successive glance. Some people have proposed what amounts to a “descriptivist” mechanism for establishing correspondence across glances. For example (Currie, McConkie & Carlson-Radvansky, 2000; Irwin, McConkie, Carlson-Radvansky, & Currie, 1994; McConkie & Currie, 1996) have suggested that on each fixation the properties of one significant benchmark are encoded and on the next fixation those properties are used to locate the benchmark through a fast search. The location of the re-identified benchmark is then used to calibrate the location in space of other items in that fixation. However this relocation-by-description idea seems implausible for a number of different reasons, even if the relocation could be accomplished in the short time available. One reason is that it ought to lead to frequent and significant errors (and failures of visual stability) when the scene is uniformly textured or otherwise free of unique features. Another is that in order for information from a pair of benchmark objects (in two successive fixations) to calibrate locations of the other items one would have to establish a metrical mapping between real 2D inner displays – a view that we have already seen runs contrary to a great deal of evidence (and which the authors of the benchmark proposal themselves eschew).

The need to build up visual representations incrementally over time brings with it the problem of establishing a correspondence between individuals in successive representations (or glances) of the visual world. Can this correspondence be established within a purely descriptive visual representation? Can we provide a description rich enough to allow correspondences to be established? Sometimes there is a unique description in a certain setting (e.g., “the object in the bottom left of the display” or “the only red object in the display”). But a description that uniquely picks out a particular individual would typically have to be changing as the object changes or moves – or else the description would have to include temporal properties (it would have to be tensed or time-stamped) which would mean that it picked out an entire temporal history of the individual (a “space-time worm”). Also the only unique description is often one that is not available to the cognitive system (e.g., numerical coordinates on the retina or in the distal scene). Even if it were possible to provide a unique description of parts of a scene, based on the immediate proximal input, there would still remain the problem of computing a mapping from this representation to the global representation being constructed. Because objects have a recursive part structure, such descriptions are typically complex tree-like structures. As a result, the mapping problem is itself generally computationally intractable (it is technically what is known as an NP-complete problem whose complexity increases exponentially with increasing size of the description). And finally, even if all such technical problems were solved, we will see in section 5.3.1 below that one would still be left without a critical causal link that determines which individual in the visual world is the one referred to in a description, even if the description uniquely specified

the individual. That's because a uniquely specifying description is different from a direct causal connection, in ways that I will try to explain later.

In addition to the above considerations, there are a number of empirical reasons to believe that in any case human vision does not work solely in terms of visual descriptions. Suppose we have a representation of some scene and then we *notice* a new property Q of some object (even assuming no intervening eye movement). In order to integrate information from the new visual episode with past information we must incrementally add this information to our visual representation. Now we have the following problem: To which object in memory do we attribute the new property Q? When we detect the new property Q, we detect it as the property of a *particular object x* – we do not detect it as occurring on some object that happens to also have property P. But, according to the pure description view, our memory representation only individuates objects by their properties (by their descriptions). If we are to increment our visual representation by adding to this description, then when we noticed that a new property Q holds of a certain object we would have to do something like the following. First we would have to find a unique descriptor of the object in question that does not involve the new property Q. Let's say that this unique descriptor is P. Then we would look for an object in memory that is represented as having property P. Assuming that this is the same object that we now noticed to have property Q, we would replace the previous description with the new augmented description that includes both the original property P and the new property Q. This, of course, assumes that the currently-unique descriptor P was the one under which the object was stored in a previous episode, which is in general not true – especially as properties change constantly. (If the representation was in predicate logic, we also have to make sure that property P and property Q are represented as occurring at the same object. The way to specify that two properties hold of the same object is by introducing an equality statement asserting that the object of which P holds and that of which Q holds are the same object.)

We have now augmented our representation of a certain object to include the newly noticed property. Now if a further property R of the same object is detected at some later time, this new augmented descriptor would have to be retrieved and checked against the current properties of the object that we just noticed as having R. If it matches, then the description would be updated to include R, and so on.³⁹ We can easily show that this could not be the process by which correspondence is established, at least in certain situations. For example, in the case of the multiple object tracking task, we showed that even if the visual system had an encoding of location on the screen for each of the objects being tracked, it could not update locations fast enough (given what we know about the speed of attention scanning) to enable 4 objects to be tracked under the circumstances involved in these experiments (see section 5.2.1, and Pylyshyn & Storm, 1988).

Notice that if we had a direct way to refer to token individuals, as well as a way to tell whether a particular token individual in view was the one being referred to, we would not run into the problem of locating and updating (momentarily unique) descriptions of objects; we would simply assert that a *particular*

³⁹ Here is a somewhat more technical way to put what I have been saying. A "pure description" can be understood in relation to descriptive statements in predicate logic in which all variables are bound by quantifiers. Thus an assertion that says an object has property P can be represented as the first-order logic expression $\exists xP(x)$. (Actually, if the description is to specify that P picks out a unique object it would have to be $\exists x[P(x) \wedge \forall y(P(y) \supset (x=y))]$.) This description does not say *which* object has property P. It is up to the visual system to find and pick it out if something further is to be made of it (but see section 5.3.1). If we augmented our visual representation by adding clauses to a pure description, for example when we notice that some additional property Q holds of a certain object, we would have to do something like the following. First we would have to find a unique description by which the object in question might have been encoded earlier, say the complex one given above. Then, on the assumption that the earlier description applies to the object that was now noticed to have Q, we would conjoin the stored description with the new property Q, resulting in the augmented description $\exists x\{P(x) \wedge \forall(y)(P(y) \supset x=y) \wedge Q(x)\}$. (Inclusion of the equality in this expression would be justified if we found the descriptor $\exists xP(x)$ stored with the object that was noticed to have Q, thus suggesting that it was the same object – so far as the visual system was concerned – and therefore we would state this equality explicitly.) If a further property, R, of the same object is detected at some later time, this new augmented descriptor would have to be retrieved and checked against the current properties of the object newly-noticed to have R. If it matches, then the description would be updated again, resulting in the new description $\exists x\{P(x) \wedge Q(x) \wedge \forall(y) (P(y) \wedge Q(y) \supset x=y) \wedge R(x)\}$. Clearly this is a grotesque way to incrementally construct visual representations.

object, say the one referred to as X_i , had certain properties and when we found out it had additional properties we would add those to the representation of that individual. Of course in that case we would need to be able to detect that a particular object that just came into view was in fact object X_i and not some other object. This, in general, may be an unsolvable problem, or at least one that clearly involves all the faculties of the cognitive system. However, so long as the object remains in view (but see Note 45) and so long as the visual architecture has certain properties (such as those I discussed in connection with the theory of visual indexes) a major subset of this problem may be solvable. This is exactly what visual indexes are for. They are there to enable vision to refer to particular token things, as illustrated in Figure 5-12.

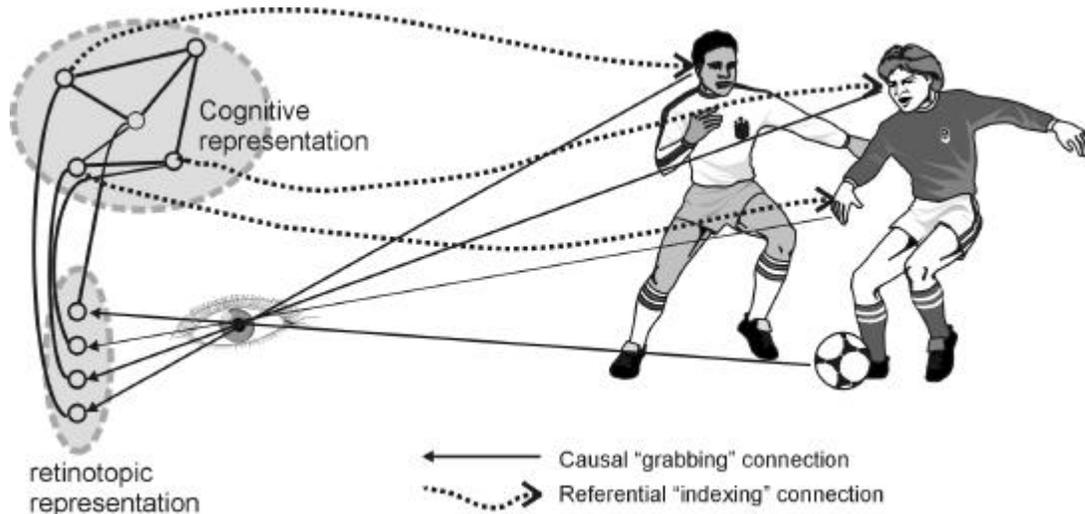


Figure 5-12. Schematic illustration of how visual representations maintain a causal connection to particular token objects in the visual scene.

5.3.1 Essential demonstratives

The problem of updating representations (and of solving the correspondence problem for individual objects over time) is actually much more complicated, and indexes or visual demonstratives are needed for more fundamental reasons than this story suggests. Consider the following two issues that I have left out of the discussion. First, as I have already mentioned, it is dubious that there always exist descriptions available to the visual system that uniquely pick out individuals. Secondly, properties of individuals change without changing the identity of the individual. Consequently, when we add the newly-noticed fact that an object has property Q, it is not enough to remember that the particular object in question had property P in the past, since it may no longer have that property now. This is certainly the case for such properties as location, since visual objects are rarely stationary, certainly not in retinal coordinates. But over time objects also change their shape, color, and indefinitely many other properties while still remaining the same object. So the description that picked out a particular individual x at time t_1 may no longer pick out the same individual at time t_2 . If the interval between t_1 and t_2 is short enough we may be able to make some assumptions about the nature of the possible changes (in the spirit of the “natural constraints” approach discussed in Chapter 2). In fact an assumption of this sort (an assumption of minimal location change) is used in the serial tracking strategy that was discussed in Section 5.2.1. This allows us to continually update such descriptions as those specifying location.

But there is also a problem with pure descriptions that is subtler and more fundamental. Despite our working assumption that we can identify token items in a scene by providing a unique description, there is in fact a gap in that story that I glossed over. Think of the visual system as sending messages to the cognitive system and vice versa (a somewhat simplified story that is close enough for our purposes). Suppose the

visual system sends the message “there is an object with properties P and Q in the scene”. Now suppose the cognitive system decides to do something that involves the object in question. If the action is a visual inquiry, it can send back the message, “does the object with properties P and Q also have property R?” But notice that vision and cognition have different sorts of access to the object. While in principle the visual component has access to *which* object is being referred to, the cognitive component can only refer to it by the descriptions provided by vision, so it is only the visual system that can pick out or identify the *particular* object token in question. This is why there is a problem about whether objects described in two separate views are the same object. Establishing a correspondence between two descriptions requires making a cross-system judgment: It requires establishing whether an object described as having properties P and Q in one description is the very same object that is described as having properties P and R in another description. If the visual system could locate objects corresponding to both descriptions in its field of view it could see whether they were the same because it could see that there was only one object token despite there being two distinct descriptions. But the cognitive system does not itself enjoy this capability; all it knows (according to the “pure description” option) is that it has two distinct representations. This dilemma leaves the cognitive system unable to refer to particular object tokens, and therefore to take actions towards a particular object token. It cannot, for example, decide to *reach* for a particular object, since, according to the pure description view, particular object tokens are not part of the representational repertoire of the cognitive system (or, for that matter, of the motor system) in the sense that in the descriptive view the cognitive system can’t represent a particular individual object *qua individual* – i.e., irrespective of its properties). The cognitive and motor systems can only represent facts about *some* object that has certain properties, not about a particular object token (understood transparently, i.e., *that* object). Another way to view this is that the two systems are stuck with different vocabularies. Only the visual system can pick out individual objects by their descriptions and it cannot pass this selection to the motor system using visual descriptors.⁴⁰

The way that we humans pick out particular unique individuals when we use linguistic descriptions is to use demonstrative terms such as *this* or *that*. Note that this way of picking out individuals requires a mechanism over and above the apparatus of pure description. It is not equivalent to individuating objects by their properties, including their locations. Whether or not picking out objects by providing location information, such as giving their coordinates in some frame of reference (see note 40) is the right way we do it is an empirical issue. But some of the evidence I have cited suggests that the human visual system independently detects, and provides access to, what I have called primitive visual objects and then (optionally) encodes various of their properties – including such properties as their color, shape and location. This does not mean, however, that location play no role. The theoretical question for us reduces to whether

⁴⁰ There are two different ways for dealing with the problem of how to command the motor system to carry out some action on a particular visible object – both of which have been adopted by robot designers and neither of which is an empirically valid model of how it is done by the human visual-motor system. One way relies on error-driven control and requires that the visual system detect both the object and the limb (or whatever is being moved) and then issue a command to move the latter in such a way as to decrease the distance between them (which means that the visual system at least needs to encode relative distances along some monotonic scale that is calibrated against the motor system). This method cannot account for the multiple-object tracking results described earlier. The other way to deal with the gap between vision and motor control is to include numerical coordinates among the descriptors generated by the visual system. An encoding of proximal location, together with an encoding of the orientation of eyes, head and body in an allocentric (global) frame of reference makes it possible to compute the 3D location of an object in space, calibrated in relation to the organism (or robot). In this way the motor system can be told where to move a limb in terms of world coordinates. However, this option assumes the availability of a complete metrical model of 3D space, including the location of objects in it, which is accessible to the motor system as well as the visual system. This is an option that we discounted on empirical grounds in chapter 1. In the absence of such an internalization of the world we are back where we started because the problem of uniquely picking out particular individuals reduces to the problem of uniquely picking out particular places in the representation. However, even if this way of picking out individuals were possible, it would not eliminate the need for demonstratives or indexes. Even if we have the coordinates of a particular object, there still remains the question of whether the object we pick out in this way is a certain particular individual object we are seeing (i.e., *this* object). We need such a fine grain of individuation because wanting to pick up a particular object is different from wanting to pick up the object at a particular location. Because our intention can include the goal of picking up *that particular thing* we must have a way to represent such an intention. This is why we not only need indexes but we have to be able to bind the indexes in two modalities – visual and proprioceptive (a problem upon which I speculated in the original expository paper; Pylyshyn, 1989).

it is possible for visual indexes to point to locations as such (i.e., to unfilled places), and that question is not yet settled experimentally (although there is some evidence that indexes can persist at a location after the object has disappeared and that at least unitary focal attention may move through the empty space between objects, though perhaps not continuously and not at a voluntarily controlled speed – see note 32 and section 6.5.3).

As a number of philosophers have pointed out (e.g., Perry, 1979), the conundrum I have just been discussing arises from the fact that a pure description is inadequate for encoding certain sorts of beliefs, in fact for encoding beliefs that depend on how and where one is situated in the world. And it is these beliefs that determine many kinds of actions. A purely descriptive representation does not connect with the world in the right way: there remains a gap between representing the fact that there is something having certain properties and representing the fact that *this very thing* has those properties. Knowing, as a point of fact, that something called the “North Star” is in line with what are called the “pointing stars of the Big Dipper” is not the same as knowing that *that* is the North Star.⁴¹ Only the latter belief will lead you to take certain actions when you are lost. In fact, the only way that knowing that the North Star can be found by extrapolating the pointing stars can be of use in locating the North Star is if we also know that *this star* and *that star* are the pointing stars. You must at some stage have a representation that connects, in this epistemically direct way, with the token objects upon which beliefs or actions must be based. John Perry gives the following nice example of how the decision to take a particular course of action can arise from the realization that a particular object in a description and a particular thing one sees are one and the same thing.

The author of the book *Hiker’s Guide to the Desolation Wilderness* stands in the wilderness beside Gilmore Lake, looking at the Mt. Tallac trail as it leaves the lake and climbs the mountain. He desires to leave the wilderness. He believes that the best way out from Gilmore Lake is to follow the Mt. Tallac trail up the mountain ... But he doesn’t move. He is lost. He is not sure whether he is standing beside Gilmore Lake, looking at Mt. Tallac, or beside Clyde Lake, looking at the Maggie peaks. Then he begins to move along the Mt. Tallac trail. If asked, he would have to explain the crucial change in his beliefs in this way: “I came to believe that *this* is the Mt. Tallac trail and *that* is Gilmore Lake”. (Perry, 1979, p4)

The point of this example is that in order to understand and explain the action of the lost author it is essential to use demonstratives such as the terms *this* and *that*. Without a way to *directly* pick out the referent of a descriptive term and to link the perceived object token with its cognitive representation, we would not be able to explain the person’s actions. The same applies to visual descriptions of the sort we have been concerned with. Unless at some point one can say the equivalent of “*this* has property P” one cannot represent particular object token in a way that will allow it to serve as the basis for action (e.g., to point towards or grasp the token object in question). But what I have called a “pure description” does not allow us to do that because it does not have the equivalent of a demonstrative.

What all this means is that the cognitive representation of a visual scene must contain something more than descriptive or pictorial information in order that it may refer to particular individual visual objects. What we need is a device for ensuring that we can find correspondences between parts of an evolving visual representation and token visual objects – the way we could if we could label individual objects in the world. What we need is what natural language provides in part when it uses names (or labels) that uniquely pick out particular individuals, or when it embraces terms like “*this*” or “*that*” – terms referred to as

⁴¹ This cumbersome wording is to make sure that the proper names “North Star” and “Big Dipper” are not given a wide or transparent reading in which they pick out particular individuals. As Jerry Fodor has pointed out to me, the sentence “The North Star is in line with the pointing stars of the Big Dipper” is ambiguous as to whether it refers to the particular individuals named “North Star” and “pointing stars of the Big Dipper” (the wide reading) or to facts about *whatever* bears those names (as in the way I rephrased it in the text). If we insist on taking the wide or rigid readings then the need for demonstratives does not arise since proper names pick out their proper referents regardless of context. Nonetheless my main point remains: You can’t do it using pure descriptions alone. You need either demonstratives or proper names that designate “rigidly.” (also see Ftn 39).

demonstratives.⁴² With such demonstratives we can refer to particulars by saying that “this” or “that” has a certain property that we can then add to our representation. In this way we can elaborate descriptions while ensuring that we continue to describe the *same thing*. In fact we can keep track of a particular individual object which changes its properties and which moves in an unpredictable way, so long as we have some means to track it *as* the same object. This latter requirement should now make it clear that the function we need is precisely the one that was postulated in our theory of visual indexes. According to our theory, visual indexes realize the equivalent of a linguistic demonstrative within the visual system.

Apart from being able to refer to particular individual objects as such, another advantage of having a mechanism such as an index is that it makes possible the use of a strategy in dealing with the visual world whereby only aspects relevant to a particular task need to be encoded. We saw earlier that the rich panorama of perceptual detail that we feel we have access to in vision is not only illusory, but also unnecessary, since the world we are observing is there before us to examine and re-examine as we need. There is considerable evidence (some of it sketched in Chapter 1) to suggest that the visual system makes use of this fact by not encoding a rich and informationally-dense panorama. Rather, it records those aspects that are relevant to some task at hand, whether it be a problem being solved or merely some theme that it is pursuing for its own intrinsic interest.

Take, for example, the study by (Ballard et al., 1997) which showed that when subjects carry out a task of reproducing a pattern of colored blocks by using a supply of additional blocks provided for the task, they appear to memorize very little of the target pattern on each glance, relying instead on their ability to move their eyes back to re-examine the source pattern. They appear to only encode something like the relative position or color of one or two blocks – far less than they could recall in short-term memory). Instead of memorizing the pattern they keep glancing back to it, picking up bits of information each time. Such a strategy (which Ballard et al. call a “deictic strategy”) is a useful one if making an eye movement is by some measure less costly than encoding and recalling several items of information.. Such a strategy is only feasible, however, if there is some easy way to keep track of *where* (in the sense of “at which object”) the relevant information is, without actually recording the details of what the information is that is at that object. This, in turn, implies a mechanism like an index. In fact it suggests that we have several such indexes (around 4 or 5), just as do the multiple-object tracking experiments discussed earlier. What would not make sense is to recall where the information was located by storing a unique description of the object in question. That would negate the point of the deictic strategy. Since there is already considerable evidence for the existence of multiple indexes in the visual system, the deictic strategy makes a great deal of sense.

5.3.2 Situated vision for robots

In the field of artificial intelligence and robotics there has been a growing interest in the use of strategies such as the “deictic” strategy discussed by Ballard et al. Some of this interest developed among investigators interested in showing that cognition is “situated” – a term used to emphasize the role played by environmental information in cognitive activity (some proponents of the “situated” camp even maintain that

⁴²There is a question here of whether the sorts of visual indexes we are interested in are more like demonstratives or more like proper names. The referents of deictic terms such as demonstratives is entirely relativized to the context of utterance. So indexes are like demonstratives insofar as they have a computable reference only in a particular context, i.e., the temporally extended one in which the referents remain continuously available to perception (although, as we have seen, because of the exigencies of the visual system, this can also include relatively brief periods of time when the objects are actually occluded). On the other hand, we also need indexes to rigidly designate objects so that we can determine their correspondence across views. Even if the objects remain continuously in view, if indexes are a type of demonstrative, there is a point when we need to conclude that *this* object is the same as *that* object. Different views are different deictic contexts, so if the index *is viewed as a demonstrative* it has a different referent in the two views and their identity has to be independently inferred. On the other hand, names refer rigidly to objects so they don’t have this problem. However, they differ from indexes in that they continue to refer even if the objects are not in view. Clearly visual indexes are not exactly like either demonstratives or like names. It’s an open question whether it’s better to say that indexes refer rigidly all the time but their referents are only computable when the objects are in view, or to say that, like demonstratives, what they refer to is relative to the context of utterance. It depends on whether you are more interested in how their semantics turns out or on how they are computed and how they function. (I thank Jerry Fodor and Chris Peacocke for sharing with me their useful – though opposite – views on this question.)

no representations of any sort are needed to guide robots Brooks, 1991, a thesis which I believe is demonstrably false even though it contains the germ of an important insight). The basic idea that the real environment provides an important basis for thinking and planned has been widely explored. For example, (Simon, 1975) describes a variety of strategies for solving the “Towers of Hanoi” problem,⁴³ one of which, minimizes memory load and is often adopted by people solving this problem, relies on the actual positions of disks on pegs as part of the memory system for planning moves and keeping track of where the current state fits into the overall problem-solving process at any particular time. The same is true of more mundane problems like addition or subtraction. (VanLehn & Ball, 1991) showed that in solving problems in simple arithmetic, subjects did much of their planning and keeping track of their subgoals by relying on the numerical display itself. The claim that Van Lehn and Ball make is that accounts of human problem solving overemphasize planning and plan following to the exclusion of what they call the externalized or situated nature of memory, and especially of goal memory. They claim that much of human behavior is “situated” rather than being “planned” where the latter refers primarily to the ideas of planning that were developed in the field of artificial intelligence in the 1970s, where formal “planning systems” typically generated completely specified plans in advance of their execution, as a series of steps to be carried out to achieve some goal (see, e.g., Georgeff, 1987). This idea of formal plan generation has come under criticism in a number of quarters as relying too little on information held in the environment. For instance it has led to the notion of “reactive planning” in artificial intelligence (Kabanza, Barbeau & St-Denis, 1997), and to the study of what is referred to as “situated actions” (Suchman, 1987). These ideas are very much in the spirit of the visual index theory inasmuch as indexes are mechanisms by which representations in memory can be integrated with information in the visual environment (as I tried to show in Pylyshyn, 2001b).

There has been considerable interest in the idea that a better way to describe the world for a robot might be in deictic terms, that is, in terms that make essential reference to such contextual concepts as “myself,” “here,” “now,” “this,” “that,” and so on, whose referents are indeterminate outside of the specific occasion of their use. Although artificial intelligence researchers rarely talk in these terms (for a notable exception see, Lespérance & Levesque, 1995), the spirit of this approach can be seen in what are sometimes called “situated vision” and or “situated planning”. The reasons for favoring such an approach are related to the reasons I have explored for needing visual indexes, and that philosophers have given for the needing “essential demonstratives” (discussed in the previous section). The alternative to the use of deictic terms is to describe the world in user-independent or allocentric frame of reference, which is not useful for purposes of performing actions on objects in this world, or navigating through it, since a global frame of reference is rarely available to a robot, and if it were available it would become obsolete very quickly as either the robot or the objects in the environment (including people and other robots) changed locations.

As I pointed out earlier in this section, a purely descriptive representation is connected with the world by semantic relations: objects in the world either *satisfy*, or fail to satisfy, the description. Consequently, the only way that a robot can tell whether something it is sensing corresponds to an item in its representation is by checking whether the description is satisfied by that part of the visual scene. Since as we saw earlier, an indefinite number of things in the world could, in principle, satisfy a particular description, this is always an ambiguous connection. Moreover it can be computationally intractable (matching descriptions is in general an exponentially complex, or what is known technically as an “NP-hard,” problem). Even in a benign world where everything remained in place except the robot, and in which the robot’s position in a global frame of reference was always known, operating successfully in such a world would depend entirely on keeping the global model in precise correspondence with the world at all times. That’s because the robot would in fact be making all decisions based on its global model and only indirectly on the perceived world. If the relevant part of the world were dynamic and the robot had to rely on visual perception to find its way around, then the problem of updating its model would become extremely complex. One solution to this dilemma is to

⁴³ The Towers of Hanoi problem has been extensively used to study human problem solving and also as an exercise in computer problem-solving courses. It involves a tower of successively smaller disks that must be moved from an initial peg to a final one, using an intermediate (third) peg to hold disks while they are being moved. The tricky constraint is that at no time must a larger disk be placed on top of a smaller one.

provide the equivalent of deictic references or indexes to certain objects, locations or properties in the scene and to allow the robot to reason using deictic terms, as suggested by (Lespérance & Levesque, 1995).

The different forms of representation that a robot could have are illustrated in Figure 5-13 below. The point is that a representation such as the one labeled (2) is inherently better for a mobile robot than the descriptive labeled (1). The literal model alternative labeled (3) is either a version of (1) or is the totally impractical proposal that the robot have a small version of the room in its memory.⁴⁴ (I will return to that class of proposal when I discuss mental imagery and mental models in Chapters 6-8). The pointers in the form labeled (2) might be implemented in various ways that need not concern us here since they need not have any psychological import. But just in case the reader is wondering whether something miraculous is being proposed consider that an obvious implementation might be to use direction-of-gaze as the main pointer and to provide a way for the robot to move its direction of gaze to where the other pointers are pointing and thus make use of direction of gaze to realize several pointers. In any case there are many technical ways of providing a functional equivalent of having several pointers. Any technique that allows either the direction of gaze or a locus of visual attention to be moved to a particular object without first having to retrieve a description of that object's properties would provide the basis for a functional pointer. (Appendix 5A even provides a partial connectionist implementation of pointers to objects on the retina).

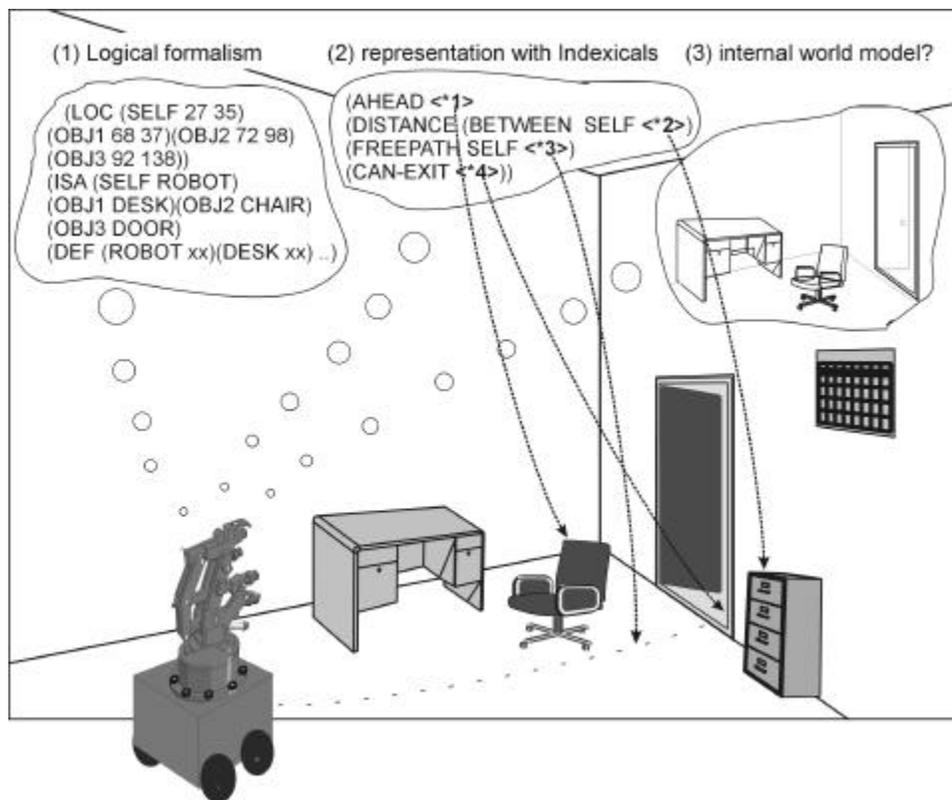


Figure 5-13. Possible ways of representing a room for a robot. The most economical is (2) which uses indexical pointers like the FINST Visual Indexes discussed in the text. (Based on Pylyshyn, 2000).

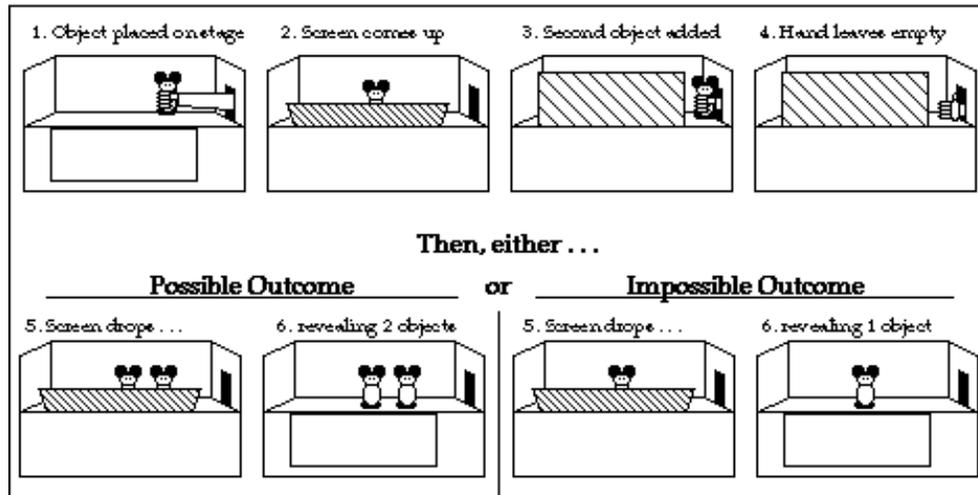
⁴⁴ While a literal model has never been seriously contemplated, a story is told that Donald Michie (then director of the Artificial Intelligence laboratory at the Edinburgh University) constructed such a device as a joke. It consisted of a toy mouse that ran around on a tabletop without ever falling off the edge and without any sensors to tell it when it approached the edge. The demonstration, which caused considerable puzzlement, allowed Michie to surprise his guests by removing the lid of the creature to reveal a small template of the tabletop and a miniature of the mouse that kept track of where the real creature was in relation to that template (essentially a small model of the table and small mouse inside the original mouse). I believe that this is as close as people have come to building a literal model-in-the-head mechanism to guide action in "open loop," although recent theorizing about mental models and mental images have come close (some machine tool controllers work from a template the way a key duplicator does, but these are not paradigm robots).

5.4 Indexes and the development of the object concept in infants

The idea of a visual index has also been used to explain some interesting findings concerning the development of the *object* concept and of numerosity (or, as some people call it “arithmetic” ability, Wynn, 1998) in infants between the ages of about 6 and 12 months (Leslie, Xu, Tremolet, & Scholl, 1998). Interestingly, at that age range, infants appear to be sensitive to the numerosity of sets of objects, although in the earlier end of this age range (under ten months) they do not seem to define individuals by their properties, but rather by something like their spatiotemporal continuity. Evidence presented in (Spelke, Gutheil & Van de Walle, 1995; Wynn, 1992; Xu & Carey, 1996) as well as more recent evidence by (Tremoulet, Leslie & Hall, 2001) suggests that at the age of only a few months, infants respond to the numerosity of items that disappear behind a screen; they do so by showing a “surprise” reactions (measured in terms of increased looking time) to a display consisting of fewer (or more) items than had earlier disappeared behind the screen.

A typical experiment is one reported by (Wynn, 1992) illustrated in Figure 5-14. A five-month old infant is shown a single doll on a stage. A screen is then made to cover the part of the stage, obscuring the doll. With the screen still covering the doll, a hand appears from the side of the stage holding a second doll, moves briefly behind the screen and returns empty. The screen is then removed revealing either one or two dolls. Wynn found that infants looked longer at the “impossible” condition in which there is only one doll (“looking time” had been shown to be related to violations of infants’ expectations). A similar sort of evidence for numerical sensitivity occurs when the number of objects decreases. Suppose the stage initially contains two dolls that are then obscured by the screen. If an empty hand moves from the side to behind the screen and returns holding one doll, then when the screen is lowered, infants look longer at the stage when there are two dolls there (the impossible condition).

(a) A '1+1 = 1 or 2' Trial



(b) A '2-1 = 1 or 2' Trial

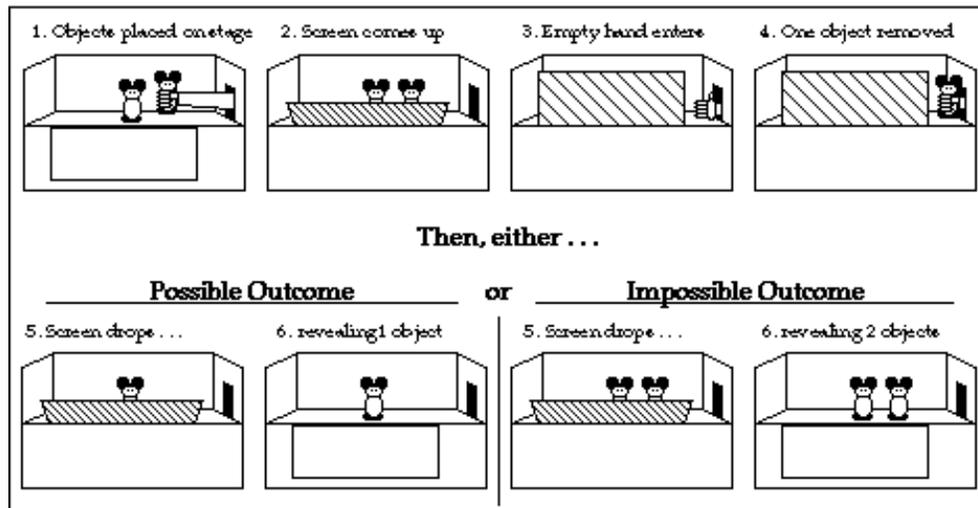


Figure 5-14: Illustration of study by Karen Wynn. In (a) the infant sees a doll become hidden by a screen. Then a hand delivers a second doll. The infant then sees one of two possible outcomes. The one labeled "impossible" leads to longer looking times. In (b) the infant sees two dolls become hidden behind the screen and then sees one being removed. Once again the infant looks longer at the outcome labeled "impossible outcome". (Wynn, 1992) interpreted this as revealing a primitive arithmetic ability in infants as young as 5 months of age.

Perhaps even more surprising is the work by (Simon, Hespos & Rochat, 1995), which extended Wynn's study by adding a condition in which the numerosity of the resulting stage contents was correct but the *type* of doll was different. Infants in this study showed no looking time differences when the identity of objects was violated, only when numerosity was violated. These basic results were confirmed by (Xu & Carey, 1996) who also showed that it mattered whether the objects were seen simultaneously or one at a time before they were placed behind a screen. Xu and Carey used two objects that differed greatly in their appearance (and which they showed could be clearly distinguished by the infants) and placed them behind a screen, one from each side. In one condition, infants saw the two objects simultaneously before they were both moved behind the screen. In the other condition they saw one being placed behind the screen and then

the other being placed behind the screen, one from each side of the stage. Then, as in the other experiments, the screen was lowered and infants' looking time was measured. Xu & Carey found that for younger infants (10 months of age) looking time was sensitive to numerosity (i.e. as revealed by their looking time to one versus two objects) *only* when they had earlier seen the two objects simultaneously, one on each side of the screen. When they had seen only one of the two objects at a time, as they were about to be placed behind the screen, they showed no preference for resulting numerosity when the screen was lowered. In contrast, older (12 month old) infants were sensitive to numerosity no matter whether they had seen the objects simultaneously or serially. This suggests that the younger infants could not individuate objects by their visual properties, but only by their being in discrete locations. More recently, (Tremoulet et al., 2001) further clarified the Xu & Carey finding concerning the distinction between simultaneous and serial viewing of objects. They used two objects that could vary in one of two colors (red or green) and in one or two shapes (triangle or circle). Like Xu & Carey, they showed that 12 month old infants could individuate objects (i.e., determine that two objects were distinct) by using differences in either their shape or their color. This was demonstrated by the fact that the infants showed a sensitivity to the numerosity of the displays when the objects were placed on the stage one at a time, so long as they differed in color or shape. The Tremoulet, Leslie & Hall studies also asked whether the infants could recognize whether the shapes and colors of the objects in the display were the same as those shown earlier (before they were hidden by the screen). They found that the infants did *not* show surprise when the final display contained a different colored object, although they did show surprise (based on their looking times) when the final display contained a different shape object. The design of this particular study is illustrated in Figure 5-15.

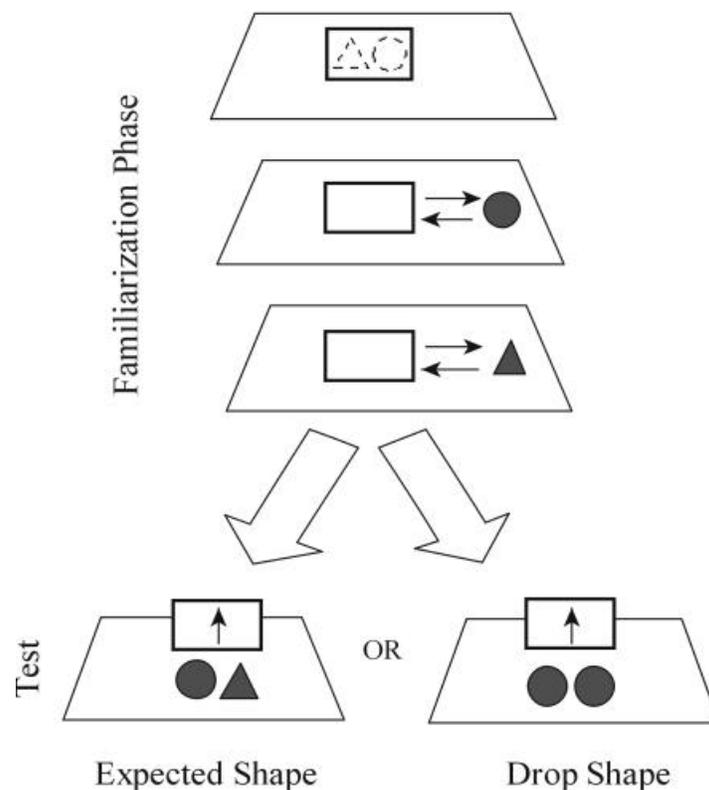


Figure 5-15: This figure illustrates the experimental condition in which objects are shown sequentially to 12-month old infants. Infants are indifferent between the two test outcomes, suggesting that they are sensitive to the numerosity of the objects but not to their shape, despite the fact that it is their shape alone that determined that there were two distinct objects. Properties used for individuating need not be the properties that are used for recognition of the objects (from Leslie et al., 1998),

What is of special interest to us is that this study suggests a distinction between the process of individuation and the process of recognition. It shows that properties that allow for individuation may be different from the properties that allow for recognition. Ten month olds in the Xu & Carey study were capable of individuating objects according to their distinct locations, but failed to correctly anticipate their numerosity when they were required to individuate them according to their visual properties. In the Tremoulet et al. study, twelve-month old infants could individuate objects by both color and shape, as demonstrated by the fact that they showed a sensitivity to the number of objects when the evidence for their numerosity was attributable solely to the different visual properties that they had (being shown a red object and then a green object was evidence that there were two distinct objects and led the infants to expect *two* objects in the final display). Despite being able to individuate objects on the basis of color and shape, and to use this information to determine how many there were, 12-month old infants could not recognize when a display failed to contain the right pair of colors. In other words they could not use color to re-recognize an object as *the same one* they had seen before. In terms of our Index theory, this suggests that the assignment of *different* indexes can make use of such distinguishing properties as differences in location and perhaps also differences in other properties, these properties need not be involved in what I have called identity-maintenance. Indeed, I have suggested that primitive identity-maintenance is a direct result of the primitive tracking capacity built into the early vision system.

(Leslie et al., 1998) explain the above findings by appealing to the theoretical construct of an “Object Index”, a construct derived from visual index theory described in this chapter. Their analysis differs in a number of ways from the one presented here (as they acknowledge). The differences lie not so much in differences between their notion of an Object Index and our notion of a Visual Index, but in their failure to draw a distinction between conceptual and perceptual mechanisms in the process of individuation. As pointed out on numerous occasions in our earlier discussion, *conceptual* individuation and re-recognition of objects is the general rule in dealing with individuation and objecthood. I have gone to some length to distinguish the traditional full-blooded sense of individuation from primitive perceptual individuation by positing the notion of a *primitive visual object* as distinct from the notion of physical object. Whether or not infants have the full concept of physical object at an early age is an empirical question, though they clearly do develop such a notion sooner or later. Indeed by about 10 months of age they appear to have the full notion of a sortal as a concept that characterizes certain kind of things in the world (e.g., dogs, cats, people, tables, toys, etc.) (e.g., Xu, 1997).

In this chapter I have focused on a more primitive sense of individuation and of tracking for two reasons. One is that psychophysical evidence suggests that there is a pre-conceptual stage of individuation and of tracking, whose character does not depend on what is known about the properties of the object being tracked. The other is that the full-blooded sense of individuation and tracking, a sense that does require appeal to a variety of conceptual (encoded) properties. Although the latter sense is more complex and sophisticated, it nevertheless must rest on certain basic built-in properties of the perceptual system that allows the properties in question to be detected and encoded. Keeping track of objects by appealing to their properties, while essential to full individuation, cannot be the whole story since as some point there must be a basic primitive “thing” or of “perceptual object” (or, in our terms, a FING) to which conceptual properties are ascribed. At some level the world, together with the nature of the visual system, must dictate what sorts of things are eligible to be sortals. The demarcation of things provided by our conceptual system, i.e., by sortal properties, cannot extend to arbitrary cuts through the physical-temporal continuum. Rather, it must capitalize on the equivalence-classes provided by the physical world, together with the nature of our sensorium. According to the view presented here, this happens through the mechanism of the visual index, which parses the physical world in a way that can be accessed by cognition and thus further analyzed and described by our system of concepts.

As to the question of whether infants have a concept of an object or whether they just track what I have called primitive visual objects or FINGs, our theory takes no position, except as just noted: No sortal-based tracking can occur without some pre-conceptual parsing of the world. This sort of parsing need not pick out such particulars as those referred to by the term “object”, but it does pick out *some* set of observer-dependent or sensorium-dependent properties. There is reason to believe that it picks out some rather odd

disjunctive collection of physical properties inasmuch as we can track patterns that we perceive as individual objects, despite the fact that their physical instantiation may be quite different from case to case, while at the same time we fail to track perfectly well-defined clusters of visual features (as we saw in section 5.2.2).

As to the data presented by (Xu & Carey, 1996) and other data cited by (Leslie et al., 1998) it is not clear whether they entail that at a certain age (less than 10 months) the child possesses the sortal “physical object” which is impoverished with regard to defining properties (other than perhaps being what some people have referred to as Spelke-Objects, after Spelke, 1990, who described them as “bounded, coherent, three-dimensional object that move as a whole...”) or whether it is merely tracking primitive FINGs, which have no such definition – and may indeed have no definition at all other than that provided by the structure of the early vision system. There are reasons for thinking it may be the latter. Sortal concepts (e.g., that of “Spelke Object”) no doubt develop early, but it is not clear that the Xu & Carey data require the assumption of an “object” sortal. The issue is, of course, whether or not infants have the *concept* of an object, or whether they have a perceptual system that enables them to track something (a “proto-object”) that is partially coextensive with the adult notion of an object. It may well be that in order to track something that disappears behind a screen no object concept is needed, for the same reason that I believe that no concept is needed in the multiple-object tracking studies described earlier. But what about the case where the object disappears behind the screen, remains there for a minute or more, and the reappears when the screen is removed (either by itself or with another object)? Is the infant’s lack of surprise due to its visual system maintaining an index directed at the occluded object during the entire time, or does the infant re-recognize the reappearing object as being in the same sortal class “object” as the object that had earlier disappeared? The data are inconclusive: Either option remains possible.

While we cannot answer this question with the available data, it is important to understand exactly what is at issue and perhaps what would count as evidence one way or the other. We know that early vision (the autonomous visual system described in Chapters 2 and 3) is a complex system that does much more than transduce the input. As we saw, it can compute visual representations in ways that appear quite intelligent. It takes into account conflicting possible interpretations and comes up with a “solution” that is often non-arbitrary (but see section 2.3.2). It computes the 2D-to-3D inverse mapping in a manner that is consistent with *our kind of world*, even though the mathematically “correct” inverse mapping is in general indeterminate (since the same proximal pattern could arise from an infinite variety of distal configurations). The operating principles used by the visual system seem to be based on a variety of built-in assumptions, often called “natural constraints”, that typically apply in our kind of world. And even though the processes in early vision are often based on local cues, they exhibit many global effects, such as the global cohesion effects found in the apparent motion of multiple elements, such as the Ternus Configuration discussed in section 4.5.4 (and modeled as a local process by Dawson & Pylyshyn, 1988). Similarly, we have seen that indexing and tracking one or more primitive objects can go on even when the objects disappear from view (Scholl & Pylyshyn, 1999; Yantis, 1995). Nothing in principle prevents early vision from carrying out such functions as tracking objects that are hidden by a screen or that go out of sight in other ways.⁴⁵ Given the sometimes surprising nature of early vision it would seem premature to conclude that these sorts of phenomena must involve the conceptual system – even if the occlusion duration of a minute or more make

⁴⁵ One might wonder what exactly the index points to when the object has left the visual scene (or the fovea). But then one might equally wonder what an index points to when the object is distributed over some region of the display (as in the studies by Rock & Gutman, 1981) or what is being tracked when the motion is illusory. It seems that the indexing system can individuate and track FINGs that are not punctate in space-time and can track them even though the object may be absent at particular instants in time and at particular places. Such results suggest that instantaneously discrete time and place may be an inappropriate way of characterizing indexing and tracking. Larger chunks of time-space may be involved, such as happens in predictive tracking using adaptive linear (e.g., Kalman) filters. Perhaps we should take serious (at least as a first approximation) the principle enunciated earlier; that indexes pick out *primitive visual objects* (or FINGs) without regard for such properties as their location, extent or duration. There is no need to be entrapped by the idea that because we view an index as a pointer it must literally point to an exact geometrical *point* in time or space. It may simply point to a FING, as defined by the architecture of early vision, the properties of which are to be discovered by empirical inquiry and which may not correspond to a simple physical description except in special circumstances. This is, after all, what happens with other ways of referring, such as using a proper name or a deictic reference (e.g., a demonstrative such as *that*).

this initially appear implausible. Whether particular cases do or do not involve the conceptual system remains an open empirical question.

5.5 How can mental particulars be bound to things in the world? Possible Implementations of the FINST indexing mechanism

I have tried to show that one needs a non-conceptual binding mechanism to connect mental particulars, such as tokens of symbols, to what I referred to as primitive visual objects (or FINGs). But how is this possible? It sounds as though I am hypothesizing something like an elastic band that connects symbols with things! In a functional sense this metaphor does capture what I am proposing. As illustrated in Figure 5-4 (or Figure 5-12), an index corresponds to two sorts of links or relations: On the one hand it corresponds to a *causal chain* that goes from visual objects to certain tokens in the representation of the scene, and on the other hand it is also a *referential relationship* that enables the representation to actually refer to those particular visual objects. The second of these functions is possible because the first one exists and has the right properties. Mental symbols refer to certain objects because those objects caused an instance of the symbol to become active – where “becoming active” is a theoretical notion that means the symbol has a role in a thought or perception that is currently being actively entertained.

How something can be both an object of thought and the end point of a causal chain needs some analysis which I must postpone for now. It should be pointed out, however, that the situation here is no different from the one that obtains in perception generally. When we perceive, our percept is of something in the world – what Gibson called a *distal* stimulus. We do not perceive retinal stimulation or the action of rods and cones, we perceive *things in the world*. But a theory of perception must deal with the fact that this perception of a distal object is accomplished by a whole chain of causal connections mediating between the distal scene and the organism’s sensors. Such a theory must include a description of processes operating over a *proximal* stimulus – or the stimulus actually impinging on the sense organs or transducers, even though we do not *perceive* the proximal stimulus.

It is this proximal aspect of the causal chain that I now address. We must ask how a visual mechanism might implement the functions summarized in Table 5-1. These include at least the following functions (a) the appearance of a primitive visual object in the field of view causes the individuation of a number of these objects, (b) the appearance of such primitive visual objects causes the activation of a small number of indexes, a unique one for each object up to a limit of about 4 or 5 indexes, (c) so long as the objects move along a smooth trajectory, these indexes continue to be maintained so that each index keeps being associated with the same primitive visual object, and (d) once an index is activated it becomes possible to interrogate each unique object to determine its properties or combination of properties – so the link has a downward as well as upward connection. I begin by viewing these requirements in a purely functional manner and describe an easily constructible black box that approximates these functions.

Consider first the question of how indexes might be evoked by the appearance of a small number of visual object in a scene in such a way that it is then possible to probe each individual object (putting off for now the question of how tracking occurs). It turns out that this function can be fairly easily accomplished by any of a number of possible mechanisms, one of which I sketch for purely expository purposes. For simplicity I provide a simple functional description of what the mechanism does. Readers who are interested in *how* one could implement such a function in a network can see some of the details spelled out in Appendix 5A. Those who are not interested in the question of how a mechanism might implement an index may skip the rest of this section altogether. The virtue of the discussion that follows is that it may both clarify what is being claimed about indexes and may serve to demystify it by fleshing it out as a particularly simple black box function.

Here is the picture of what the simple mechanism does. Think of the mechanism as consisting of boxes such as shown in Figure 5-16, in which an array of detectors provides the inputs (notice that this array does not need to be topographic, so that neighboring elements in the array correspond to neighboring places in the world – in fact if the connections to the array were scrambled it would work just as well – see note 47).

These will need to be more than just luminance detectors, so the source of the input should be thought of as more like Wolfe's Activation Map (Wolfe, Cave & Franzel, 1989) or Treisman's Feature Maps (Treisman & Gelade, 1980). The way it works is that the middle box detects the n most active of the input lines (I have set $n=4$ for illustrative purposes). When it has done this it lights up n of the lights shown on the box. For this illustration, assume that the first light corresponds to the most active input line (whichever that might be), the second light corresponds to the second most active line, and so on. Beside each light is a button. These buttons allow a signal to be sent back to the source of the input lines as follows: when you press the first of these buttons it sends a signal to the input element that activated the corresponding detector and resulted in the first light to coming on. Pressing the second button sends a signal to the element that caused the second light to come on, and so on. Notice that whoever (or whatever) presses the button does not know *where* the signal from the button will go, only that it will go to whatever caused the corresponding light to come on (this ensures that two buttons do not send a signal to the same detector).

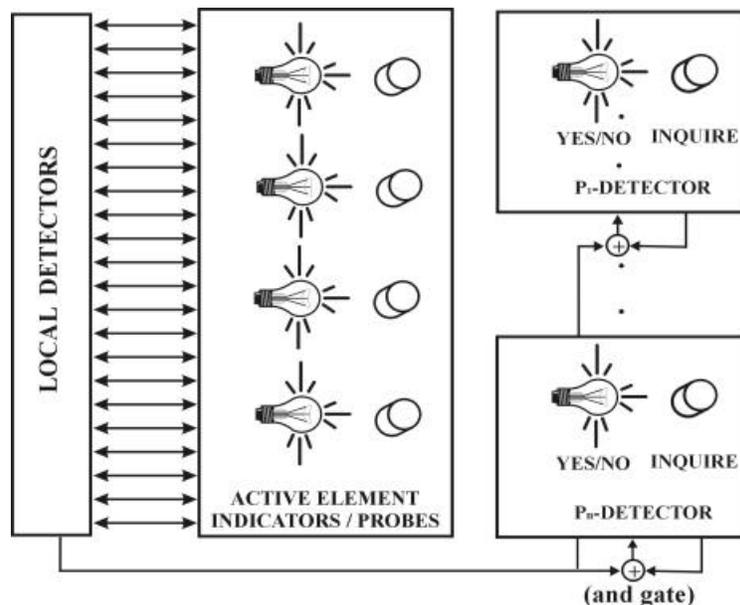


Figure 5-16: Sketch of a possible "black box" implementation of a FINST mechanism.

The function just described is the heart of the operation of our sketchy indexing system, for it provides a way to "probe" particular elements in the input and this, in turn, provides a way to ask about certain of its detectable properties (i.e., particular properties of particular elements in the input). The only other mechanism we need in order to realize that function is provided by a set of global detectors for properties P_1, P_2, \dots, P_m each of which is connected to every element in the input. We arrange for the property detector to fire only if the (unique) element being probed by the system just described has property P_i . This requires that there be number of YES/NO P-DETECTOR indicators and P-INQUIRY buttons⁴⁶ for different properties P_i as well as a bit of simple logical circuitry. The idea is simple: a P-DETECTOR fires only if it gets two or more inputs. One of these comes from an input element that has property P_i and the other comes from what we called the probe, which originates with the buttons on the central ACTIVE ELEMENT box. If (and only if) the item being probed has the property being inquired at the P-DETECTOR button, the light on the corresponding P-DETECTOR indicator will be illuminated. Thus the procedure for using this black box requires two hands: If you want to know whether a particular element –

⁴⁶ We have arbitrarily decided that the P-Detectors are active inquiry systems, rather than passive transponders. In the latter case *all* property indicators for properties of the probed element would light up. It seemed more plausible that indexes are used to inquire about particular properties of indexed objects rather than be told of all properties of these objects at once, since there may be a very large number of potential properties. Nonetheless the choice between these two schemes is an empirical matter and not a matter of principle.

one that was salient enough to cause light X_i to come on – has property P_i you press the button beside light X_i and also press the button marked “P-INQUIRY” for property P_i . The P-DETECTOR indicator will then light up if the element associated with light X_i has property P_i . This protracted description is presented to make only one point: It is easy to make a circuit that tells you whether an active detector element has a particular property, *even if you don't know anything about the active element in question* (e.g., where it is located).

This gives us what we want of our indexing mechanism: a way to inquire directly about particular properties of certain salient items without first having to locate the objects. It even allows one, for example, to ask whether a particular salient object has both property P_i and property P_k . Just press both the P-INQUIRY buttons while pressing a button on the main box corresponding to an active object: if the P_i and P_k indicators both light up it means that there is an object that has both property P_i and property P_k . Notice also that when a light is illuminated on the main box it tells us only that *some* primitive visual object is bound to an index. When n lights are illuminated it tells us that n distinct primitive objects are bound to distinct indexes. Beyond that the illumination of a light does not tell us *anything* more about that object (even the ordinal position, which I spoke of as marking activation ranking, is incidental and invoked only as a way to temporarily keep the objects distinct). In particular the box provides no information about the location of objects that caused the lights to come on. Certainly the circuits inside the box must make the connections to the appropriate locations, but this information is unavailable to the outside. In this way the box comes very close to providing the function of indexing a number of primitive objects in the input matrix in such a way as to allow the indexed objects to serve as arguments to visual predicates.

The alert reader will notice that as it stands this box does not quite meet all our functional requirements. That's because what is being selected and inquired-of in this case is a particular (stationery) point of a spatial (topographic) matrix. It is not an object in the world, inasmuch as the system does not keep addressing the same distal cause of activation as the proximal projection of the latter moves around in the array. But this can be changed so that functionally the system in Figure 5-16 behaves as required by the Indexing theory – it will keep addressing (interrogating) a moving item in the input matrix as long as that item moves in a trajectory that meets certain constraints (the nature of which are a matter of empirical inquiry). It is not technically difficult to arrange matters so that the particular input element that is probed by a particular probe button changes appropriately to correspond with continuous movements of the pattern of stimulation in the input. It is simply a matter of providing some mechanism, operating over local neighborhoods of the input, which ensures that the same connection between cells and lights/buttons is maintained when adjacent cells become activated/deactivated (i.e., when the activation maxima move continually over the spatial matrix).⁴⁷ When property-inquiries are carried out in such a system they would normally detect properties associated with the same moving object. When two properties are detected in association with the same index (i.e., the same light), these will be joint properties of the same object. The function of the box shown in Figure 5-16 therefore mirrors the properties required of indexes – including automatic selection of primitive visual objects, and object-based or “sticky” indexes that are transparent to object location.

In Appendix 5A I discuss a possible statistically-based mechanism, using spreading activation, that enhances neighboring elements in the matrix and increases the chances that they will become associated with the same indicator light and thus will be the target of the same probe inquiries. This provides a rough tracking mechanism for continuous smooth motion. Many different mechanisms could be imagined that can track a continuously moving patterns of local excitation maxima – including a parallel predictive mechanism based on techniques such as Kalman Filters (e.g., Lee & Simon, 1993) or parallel mechanisms that compute apparent motion over brief disappearance of the objects (such as those proposed for apparent motion by

⁴⁷ When I refer to a “map” or a “matrix” in the present context I make only weak claims about its spatial character. The only spatial properties that such a map needs to have is (a) the detectors have to be spatially local (i.e., they have to have limited receptive fields) and (b) there must be connections between individual detectors and the detectors of neighboring sites, only because the notion of “neighborhood” plays a role in the suggested mechanism for favoring continuity of motion. The actual units in the mechanism illustrated in Figure 5-16 do not themselves have to be situated in a 2D spatial array and indeed the operation of the mechanism illustrated here is indifferent to the input being spatially scrambled, as long as immediate-neighbor connections are preserved.

Dawson & Pylyshyn, 1988). The only constraint that we impose on such a mechanism is that it should work in a bottom-up fashion and therefore should operate on the basis of *local information support*. This means that any predictive tracking should be based on spatially local information. Beyond that the tracking mechanism can take into account any property of the movement of the activation pattern and can in principle even track objects that disappear behind an occluding surface in certain ways or that produce apparent motion. Sometimes surprisingly global patterns can be computed in this way. For example, a mechanism for computing apparent motion proposed by (Dawson & Pylyshyn, 1988), operates on the basis of strictly local information and yet predicts many apparently-global effects of apparent motion (such as the preference for coherent group motion).

The network shown in Appendix 5A illustrates a possible implementation of this mechanism. This implementation is not in itself of particular interest except as an existence proof that the function being assumed is realizable in a simple network based on local-computations (such as would be expected in the nervous system) and that such functions as enabling selective probing of moving objects can be accomplished without first *locating* the objects in question, at least in the sense of encoding their coordinates.

Appendix 5A: Sketch of a partial network-implementation of the FINST Indexing mechanism

The function described in section 5.5 can be implemented in a network of simple elements. Such networks are sometimes referred to as Artificial Neural Networks, but I do not make any such neural claim. What is important about this network, from our perspective, is that it illustrates how a simple mechanism can realize the function described earlier (and therefore can approximately realize some of the properties of the FINST indexing mechanism) while operating with the kind of input that is natural for the visual system, at least to a first approximation. The network I have in mind uses a slightly modified version of what is known as a fully connected Winner-Take-All (WTA) network. Such a network has the property that when provided with an array of inputs that vary in their activation level (i.e., that have different magnitudes of inputs) the network settles into a state in which the unit with the most highly active input retains its value while the activity level of all the others is reduced to zero. This is, in fact, a maximum-finding circuit. Since we usually don't want the values of the actual input sensors to be changed, we think of the sensor units as copying their values into a duplicate array known as a buffer array. So far the picture is like this (Figure 5-17). An array of retinotopic sensor units activates an array of buffer units. Each of the buffer units feeds into a unit of a WTA network. The network operates iteratively and eventually settles into a state where all the buffer units have value zero except the one that received the largest input from its corresponding sensor.⁴⁸ When this happens, the network signals its success by generating an output (in some versions it might only generate such an output if the maximum input value exceeds some threshold).

⁴⁸ The simplified version of the network described here – in which each unit is connected to every other unit – is unsatisfactory for a number of reasons (e.g., it is not guaranteed to converge, the number of connections grows exponentially with the number of units, etc.). There are various alternative ways to implement such a network that overcome these problems, one of which is described by (Koch & Ullman, 1985). In addition, it may be desirable for a number of reasons to arrange the connectivity to emphasize closer units, for example by having the density of connections fall off as the distance between units increases. This helps the smooth-tracking problem by preventing indexes from “jumping” to remote but more active inputs.

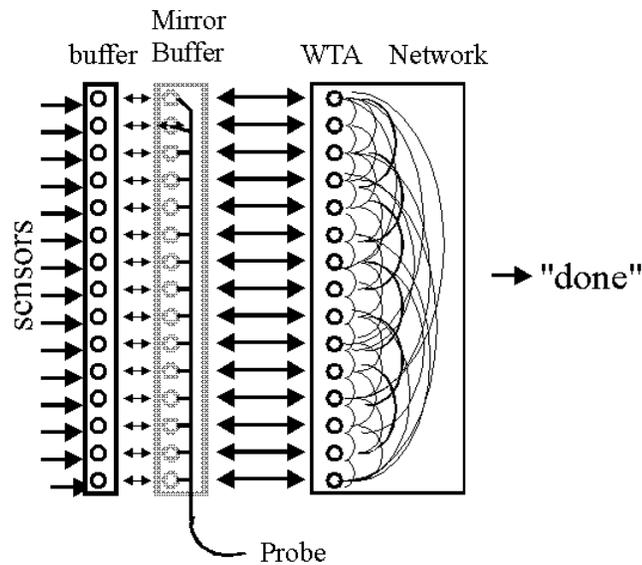


Figure 5-17: Winner-Take-All “maximum-finding” network, the first step to a possible mechanism for implementing FINST Visual Indexes. WTA is a completely interconnected network in which each unit inhibits all the others.

We now have an array of sensors and also a buffer that contains the maximum value of the highest input and nothing at all on other inputs. This network allows us to send a signal (call it the “probe signal”) to the input buffer unit that has the maximum input and to no other unit. This is how it works. Suppose there is another array of units situated alongside the buffer units. Call these the mirror buffer. Each unit in the mirror buffer receives inputs from its corresponding buffer unit, which it sums with the probe signal. If the sum exceeds a threshold, then mirror buffer unit fires and transmits a signal along the input line associated with that particular input. This probe signal only reaches the buffer unit that had the maximum signal value at the outset. Figure 5-18 below shows the connections among the relevant units that have survived the WTA reduction. If a probe signal is sent to all the mirror buffer units, only those that arrive at a surviving (selected) one are passed on. This is how a probe signal can be directed to just the unique input line that was selected by the WTA circuitry. Since I have not said what the magnitudes of the inputs represent, I have left it open what properties cause the probe line to be connected to the winning object. But once the probe circuit is connected in this way it can be used to *interrogate* the selected line.

The way this “interrogation” is done is by using threshold units, as we did when we directed the probe signal to the maximum unit (this is exactly like the way modern computer memories are interrogated using what is called a “strobe” signal). We assume that we have a unit that detects particular property, such as “red”, or “circular”. In its quiescent state it requires two inputs to fire and once it fires it sends a signal to the listening post. If we want to know whether the *selected object* is red all we need to do is send one unit of signal to the probe and one unit of signal to the “red” detecting unit. If we get a response at the listening post that means that the very unit that was selected by the WTA circuit had the property “red”. The figure below shows the bits of circuitry that are present at the selected buffer and mirror buffer units which allows the interrogation of these units for particular properties (in the case show it is the property of being red).

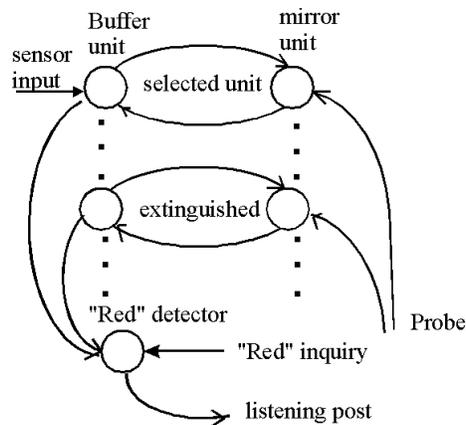


Figure 5-18: Detail of the connections at the selected (and one unselected) buffer and mirror units. To see whether the selected input line (i.e., the visual object that caused the WTA network to converge) has the property “red” you send a signal simultaneously on the probe line and the “red” inquiry line and watch to see if you get a signal at the listening post.

The point of this exercise is simpler than the details might suggest. It is to show that once you have figured out what properties of objects are treated as salient (and cause the network to converge) it is easy to think of ways to use such a network to allow a signal to be sent to the input that is selected in this way, and thereby to test the selected input for specified properties. The use of such a probe signal to check the property of unknown objects is sometimes referred to as strobing, by analogy with a technique in computer engineering. There is nothing special about this particular implementation. It is presented here merely to show that nothing clever or mysterious is being assumed. It is important to notice that this elementary circuit allows an element to be interrogated without any information about it other than that it was the most active unit. In particular it provides a way to test for properties associated with a unit *without knowing where that unit is*. No part of the system contains the coordinates (or any other location information) of the unit whose associated properties are being tested. A place in retinotopic space is thus addressed without specifying any property that holds of it, except that it is highly active – just as required by the visual index theory.

Of course as it stands, this network does not track a moving object, nor is it able to select several objects at one time. Neither of these limitations is irreparable. For example, it is easy to augment the network so it can follow a moving signal – in fact one possible technique was described in the (Koch & Ullman, 1985) paper. The propensity of an input to be selected by the WTA network depends on the magnitude of its activation signal – the source of which I have left completely unspecified (although it can easily assimilate the assumptions in such theories of attention as Wolfe’s Guided Search Model – Wolfe et al., 1989). Consequently anything that increases the input that a particular buffer unit receives will tend to make it a more likely candidate for selection. One possible source of augmentation of the input, suggested by (Koch & Ullman, 1985), is activation from spatially nearby units. It is easy enough to arrange for each selected unit to pass activation to its immediate neighbors. The consequence of this type of connection is to give the region surrounding a selected object greater favor for subsequent selection. What this means is that if an object moves smoothly across the display it will keep enhancing its immediate neighborhood, leading to tracking. This is a very crude means of causing a certain type of tracking behavior. It is like tracking the bump when the cat is moving around under a blanket. Other locally-based activation mechanisms are also possible. For example, (Dawson & Pylyshyn, 1988) present a model of apparent motion based on summation of labeled information from neighboring units. The resulting network displays apparently global properties – such as increasing the likelihood of apparent motion occurring in a manner consistent with the natural constraint of coherence of matter – but based entirely on local information from neighboring regions. Similarly, (Pylyshyn & Eagleson, 1994) proposed a network that used local predictive filtering (based on Kalman filters) and enhanced the likelihood of selecting inputs that are on a predictable trajectory. The

point here is that tracking is compatible with a locality constraint on selection. Tracking does not require that objects having certain visual properties first be identified and a correspondence established. Tracking can be carried out by processes that only have access to information in an immediate local neighborhood. In this way tracking can be accomplished entirely by a bottom-up process.

The alert reader might notice that these activation-spreading mechanisms only increase the likelihood that a neighboring element is selected next. This would still leave the question of whether this element is the *same* one as was selected earlier, and if so what makes it the same one. Notice that as far as the mechanism I have described is concerned, a *different* index might be assigned to the nearby element as a result of the spreading activation. In order for the network to keep tracking a moving element the element has to keep being attached to the same index. How does one ensure that nearby elements keep the same index? Within the context of the network model of indexing, this too can be viewed as a technical (as well as an empirical) problem rather than a matter of principle. Both the multiple-object indexing and the same-index tracking problem might be solved by the same design principle. For example, if buffer units were randomly connected to other buffer units so that the probability of a connection between a pair of units was great the closer the units were to one another, then we might prevent indexes from jumping to more distant units that had higher immediate activation. This would favor spatial-temporal continuity in assigning particular indexes.

As it stands, the network is also incapable of tracking multiple independently-moving objects, as required by Indexing theory. If we had several networks such as the one discussed above they would converge on the same object so the problem that needs to be solved is how to keep the different objects distinct – or how to prevent distinct visual objects from capturing the same *index*. But once again alternative ways to solve this problem are available. For example, (Acton, 1993) developed a multiple-object tracking version of the network by using time-based marking. The most highly activated object captures the first index and then enters a refractory period while the second most active object captures the next index. The indexes are synchronized to a clock, which provided an easy but not very satisfying solution to the index separation problem (since it requires a clock to pulse the network). While this particular solution may not be very attractive, it does point out that alternative implementations are easily found within the WTA paradigm and offers an existence proof of the realizability of the indexing proposal. Also varying the density of connections as a function of distance, as suggested above, could prevent two distant active units from grabbing the same index. Other mechanisms include capitalizing on a process known as Inhibition-of-return, wherein an activated or attended object inhibits reactivation for a period of time (as in the well-known refractory period between nerve firings).

6. SEEING WITH THE *MIND'S EYE* 1: THE PUZZLE OF MENTAL IMAGERY

6.1 What is the puzzle about mental imagery?

In earlier chapters I discussed various connections among the world, the visual system, and the central cognitive system that is responsible for reasoning, inference, decision-making and other rational processes. In the course of this analysis we have found much that is counter-intuitive about how the mind is organized and how it connects with and represents the world. Yet nowhere does our intuition go astray more than when we consider what happens when we recall a past event by imagining it or when we reason by imagining a situation unfold before our “mind’s eye.” Our introspection is very persuasive here and it tells us quite unequivocally that when we imagine something we are in some important sense *seeing* it and that when we solve a problem by imagining a situation unfold in our “mind’s eye” we have but to pay attention and notice what happens. No intervention on the part of reasoning appears to be involved in this process.

Imagine a baseball being hit into the air and notice the trajectory it follows. Although few of us could calculate the shape of this trajectory none of us has any difficulty imagining the roughly parabolic shape traced out by the ball in this thought experiment. Indeed, we can often predict with considerable accuracy where the ball will land (certainly a properly situated professional fielder can). It is very often the case that we can predict the dynamics of physical processes that are beyond our ability to solve analytically. In fact they may even be beyond anyone’s ability to solve analytically. Consider the behavior of a coin that has been spun on its edge. As it topples it rolls around faster and faster until, with a final shudder, it lies still. The behavior of this coin, which accelerates as it loses energy, has only recently been mathematically solved (Moffatt, 2000). Yet many people can imagine the behavior in question when asked to visualize the situation. Why? Is it because their imaging mechanism inherently obeys the relevant laws? Or might it perhaps not be because, under the right circumstances, they recall having seen a dropped coin behave this way? The intuition that it is automatic is very strong. There seems to be something automatic about how the action unfolds in one’s image and the impression that vision is involved is similarly very strong.

Imagine that you climb a ladder and drop a ball from a ten-foot height. Observe it in your mind’s eye as it falls to the ground. Now do the same while imagining that you drop it from a five foot height. Does it not take longer to fall to the ground from a height of ten feet than from a height of, say, five feet? How much longer, do you think? You could actually measure the time it took for the ball to drop in your imagined scenario and get an exact answer which would surely confirm that it takes longer to drop from a greater height. You could even plot the time as a function of distance and perhaps even as a function of imagined weight (and you would probably find, as Ian Howard did, that the time was proportional both to the height and to the weight – unlike what would happen if you actually dropped a real ball⁴⁹). Now imagine that you are riding a bicycle along a level road, peddling as hard as you can. Then imagine you have come to a hill. Does the bicycle not slow down without your having to think about it? What about when you come to the downhill side of the hill? You can even stop peddling completely and you will probably find that the bicycle in your image continues to speed down the hill.

The illusion of the autonomy of the imagined scene is even more persuasive in the case of purely visual or geometrical properties. Imagine a very small mouse in the far corner of the room. Can you easily see

⁴⁹ In a series of unpublished studies, Ian Howard of York University, showed that people’s naïve physics, as measured by their predictions of falling objects, conformed to Aristotelian rather than Newtonian or Galilean principles. Howard dropped metal rings of various sizes behind an opaque screen and asked subjects to catch them by poking a rod through one of several carefully located holes in the screen provided for the purpose. The measured times showed that subjects assumed a constant velocity, rather than the correct constant acceleration, and that the assumed velocity increased with the weight of the ring, contrary to Galilean principles (i.e., that objects fall with constant acceleration, rather than constant velocity, and the acceleration is independent of mass).

whether it has whiskers? Now imagine that you are very close to it (perhaps it is in your hand). Isn't it much easier now to see whether it has whiskers? Close your eyes and imagine you are looking at the bottom left corner of the wall in front of you. Now imagine that you shift your gaze to the upper right corner. Did your gaze move through the intermediate points as you shifted from one corner to the other? Did you notice any of the things on the wall as you shifted your gaze? Do you think it would have taken you longer to shift your gaze if the region you were imagining had been smaller (say confined to just a picture on the wall)? Imagine a rectangle and imagine drawing the diagonal from the bottom left corner to the top right corner. Now imagine drawing another line, from the top left corner this time, to the middle of the right-hand side. Does this second line cross the first one you drew? And if so, does it cross it below or above its midpoint? Did you have to do any geometrical analysis to answer that question, or did you just read it off your image? Imagine an upper case letter **D**. Imagine it rotated counterclockwise by 90 degrees. Now imagine the letter **J** attached to it from below. What is the shape of the resulting combined figure? It seems as though you can do this entirely in your mind's eye and "notice" what the combination of the two figures "looks like" an umbrella without thinking about it. Such examples seem to show that mental imagery has a "life of its own" and unfolds without your rational intervention. They also seem to show that imagery makes use of the process of *visual* recognition. But does it? One's intuitions about all these examples notwithstanding, there is much more to what your mental image does and what it "looks like" than meets the eye – even the "mind's eye". As we saw in Chapter 1, the more familiar and vivid our experience of our inner life is, the less we can trust our impressions to provide the basis for a scientific theory of the underlying causes of those mental activities. I will return to more examples of this later.

Oposing the intuition that your image has an autonomous existence, and unfolds according to its own laws and principles, is the obvious fact that it is *you* alone who controls your image. Perhaps, as (Humphrey, 1951) once put it, the assumption that the image is responsible for what happens in your imagining puts the cart before the horse. It is more likely that the image unfolds as it does because you, the image creator *made* it do so. For example, does it not seem plausible that the way things unfold in your image is actually guided by what you know would happen in real life? You can imagine things being pretty much any size, color or shape that you choose and you can imagine them moving any way you want. You can, if you wish, imagine a baseball sailing off into the sky or following some bizarre path, including getting from one place to another without going through intervening points, as easily as you can imagine it following a more typical baseball trajectory. You can imagine all sorts of impossible things happening – and cartoon animators frequently do, to everyone's amusement. The wily coyote chasing the roadrunner runs onto what turns out to be a picture of the road or sails off the edge of the cliff but does not fall until he sees that there is no support under him. Or the roadrunner sees the coyote approaching and suddenly appears behind his back. We can easily imagine the laws of physics being violated. In fact unless we learned certain Newtonian principles of physics we do not even correctly imagine what happens in certain real situations – such as in the earlier example of the time course of an object falling to earth. So if we can imagine anything we like, why do we imagine the things we do in certain circumstances? Do we imagine things happening in a certain way merely because we *know* that this is how they would happen? What if we can't predict how they will happen without going through the process of imagining them; does this mean that imagery contains different kinds of "knowledge" than other forms of representations? And what, in turn could that mean? Is it that imagery involves the use of *different* sorts of reasoning mechanisms? Sometimes it feels as though we can imagine pretty well anything we like, but is that so? Are there events, properties or situations that we cannot imagine, and if so, why not? While we can imagine the laws of physics being violated, can we imagine the axioms of geometry being violated? Try imagining a four-dimensional block or how a cube looks when seen from all sides at once or what it would look like to travel through a non-Euclidian space. Before concluding that such examples illustrate the intrinsic geometry of images, however, consider whether your inability to imagine these things might not be due to your not *knowing*, in a purely factual way, how these things might look. The answer is by no means obvious. For example, do you know where various edges, shadows and other contours would fall in a four-dimensional or non-Euclidean space? If you don't know how something would look, then how could you possibly have an image of it, since having an image of something *means* to imagine how it *looks*. It has even been suggested (Goldenberg & Artner, 1991) that certain deficits in

imagery ability resulting from brain damage, are a consequence of a deficiency in the patient's knowledge about the appearance of objects. At the minimum we are not entitled to conclude that images have the sort of inherent geometrical properties that we associate with pictures.

We also need to keep in mind that notwithstanding one's intuitions about such examples, there is reason to be skeptical about what one's subjective experience reveals about the nature of a mental image (both its content and its form). After all, when we look at an actual scene we have the unmistakable subjective impression that we are examining a detailed panoramic view, yet as we saw in Chapter 1, there is now considerable evidence that we visually encode very little in a visual scene unless we explicitly attend to the items in question and that we do that only if our attention or our gaze is attracted to it (Henderson & Hollingworth, 1999). Notwithstanding our phenomenology, the evidence suggests that we do not encode a great deal of detailed information about a visual scene. Moreover, the information we do have about a scene does not appear to be in the form of a global picture, for reasons discussed in chapter 1, sections 1.3.3 and 1.3.4 (e.g., because non-retinal information appears to be much more abstract and conceptual than retinal information, because information from successive glances cannot be superimposed, and so on). It would thus be reasonable to expect that our subjective experience of mental imagery would be an equally poor guide to the form and content of the information in our mental images.

What needs to be kept in mind is that the content of our mental images, both the explicit information it contains and the dynamics of how that changes, is the joint consequence of (a) what we intend our mental image to show, (b) what we know about how things in the world look and how they tend to unfold in time, and (c) the way our mind (or perhaps only the part of it that specializes in mental imagery) constrains us (there are some other possible extrinsic reasons as well – see Section 6.3.4). Discovering the boundary between the major determiners of image content (in particular, between what we *know* or *intend* and the constraints imposed by the mechanisms or the particular form of representation used – in other words, by the way our brain is structured) is the central problem in the study of mental imagery. Both the impression that we can imagine whatever we please and the impression that our images have a life of their own are illusions. Our task as scientists is to try to steer our way between the Charybdis of total plasticity and the Scylla of the autonomous unfolding. This task is no different from the one faced by cognitive scientists in every area of cognition since what we can and do think is similarly a joint consequence of the plasticity of thought (we believe we can think any thought there is to think) and of the constraints imposed on them (on what we can represent, conceptualize, or infer) by the nature of mind. The latter type of constraint arises from what we call the *cognitive architecture* and we will have more to say about this concept later. In the case of the particular cognitive activity that is accompanied by vivid experiences, such as the experience of seeing an image in our mind's eye or experiencing ourselves thinking in sentences of our language, the temptation to reify the experiential content into a theory of the form of our representations seems very nearly inescapable, leading to the ubiquitous view that the mind has two distinct modes of thought: linguistic and imagistic (or pictorial). In fact these two ways of experiencing our thoughts neither exhaust the ways in which we can think nor do they provide a useful characterization of what thinking consists of – but more on this in the Chapter 8. It is precisely the power of introspection to, on the one hand, provide a window into what we are thinking *about* and, on the other hand, mislead us into believing that we can see the *form* in which our thoughts are encoded and the nature of the thinking process itself that creates difficulty in coming to an understanding of the nature of perception and thought. It is the main reason why there is a ubiquitous problem of grasping what a scientific theory of reasoning with mental images might be like.

The view to which we are tempted by our introspection is the view discussed earlier in Chapter 1 (and which Dan Dennett has called the “Cartesian Theater” view of the mind). It is the view that when we think using mental images we are actually creating a picture in our mind. And when we reason in words we create sentences in our mind. In both cases there is the concomitant assumption that someone (or something) perceives these pictures or sentences. Henceforth I will refer to such views (at least as applied to the visual modality) as the “picture theory” of mental imagery. This is sometimes contrasted with an alternative that posits symbol structures, of the sort that appear in artificial intelligence or other computational models. There are very good reasons for believing that thought takes place not in language or images, but in what has sometimes been called the “language of thought” or *lingua mentis* (Fodor, 1975). For present purposes

I will not be concerned with the details of an alternative theory of the mental structures that underlie the experience of mental imagery. Rather I will be concerned to show that the intuitively appealing *picture theory* is implausible. I will do so by arguing that none of the phenomena and experiments distinguish between a picture theory and the class of symbolic or “language of thought” possibilities. Because the latter are needed to explain non-imaginal thinking and reasoning, I will take the view that thoughts have the same form regardless of how they are experienced as our “null hypothesis”. The question then, is whether any of the arguments or empirical evidence suggest that we should reject this null hypothesis.

But why should we shun the intuitively appealing view in favor of something so ill defined and apparently counter-intuitive? In chapter 1 I alluded to some of the reasons why in the case of visual perception, the intuitive view is inadequate and incapable of accounting for the empirical facts. Before elaborating this argument and extending it to cover the case of mental imagery, let us stand back and try to get a broader picture of the problem of mental imagery that needs explaining. Before doing so, however, I do want to clarify one point that is often misunderstood. Contrary to what many critics have assumed this means, I do not claim that images do not really exist or are merely “epiphenomenal” (Shepard, 1978b). The notion of something being an epiphenomenon is itself misleading. Usually what people mean when they accuse me of making this claim is that they do not agree my view (as Block, 1981 #25, has correctly pointed out). There can be no question of whether the experience of imagery exists nor even of its phenomenal character. The question concerns the explanation of the causal events that underlie this phenomenal experience. In cognitive science, these causal events take the form of information processing operations performed on some representations. The explanation of what underlies the way this process works need not, and in general will not, appeal to how they are experienced – to the fact they appear to us to be like pictures of the scene we are imagining. This is very much like saying that the way physical objects look to us is not part of our theory of how they take part in physical and chemical reactions. For that we need a different theory, a theory of their underlying causal structure, which always adverts to invisible things and invisible properties and forces.

Of course the phenomenology is also interesting and one may be able to tell a fascinating story about how things appear. In fact (Shepard, 1978a) has done a remarkable job of illustrating many of his hypnagogic (near-sleep), entoptic (externally, but not optically, caused), and dream images. These are fascinating accounts, but it is not clear how they should be taken within a causal theory. In commenting on my paper on mental imagery, (Dalla Barba, Rosenthal & Visetti, 2002) remark that phenomenology was never intended to provide a causal explanation. What it does is provide an account of how things are experienced, and in so doing they show how some experiences are like others (they provide a taxonomy of how things appear). On the basis of their (and other writers’) phenomenal experience of mental imagery and of perception, they conclude that images are pictorial but that they do differ significantly from the experience of vision. Whether phenomenally based taxonomies can be accommodated in an information-processing theory, or can help to decide among alternative theories, is at present an open question (both in the study of mental imagery and in the study of vision).

The most important idea that must guide us in trying to understand the nature of mental imagery is the one just alluded to: It is the fundamental question of which properties, characteristics, mechanisms, etc are *intrinsic* or *constitutive* of having and using mental images, and which arise because of what we believe, intend, or otherwise attribute to what we are imagining (to the *content* of the image or to the situation being imaged). The central question we need to ask is which aspects of “visual” or imaginal (or imagistic) thinking occurs because of the special nature of the imagery system, rather than because of the nature of thinking in general, or because of our tacit knowledge and how it is organized, or the nature of the task or of the subject matter of our thoughts. We need to ask, for example, whether what is special about imaginal thinking might simply be the fact that mental imagery is associated with certain content or subject matter, such as the optical, geometrical properties or the appearances of the things we are thinking about, and not on the way the information is encoded or on special mechanisms used in processing it. Notice that it *could* be the case that when we think about spatial layouts, or about the appearance of objects (e.g., their shapes and colors) or other visual topics that tend to elicit mental images, we find that certain psychophysical phenomena are observed due to the fact that we are then concerned with concrete visible properties rather

than abstract properties. This would be no different from finding that certain properties (like differences in reaction times to different words or the ability of different secondary tasks to interfere with the thinking) are observed when we think about economics or music or health. It is plausible that when you are solving problems in economics your performance is degraded by secondary tasks involving economic concepts, the way that thinking about spatial topics is disrupted by tasks which themselves involve spatial concepts. Differences attributable to the *topic* of thinking are not what those who postulate a separate image system have in mind.

Clearly there are important distinctions to be made before this discussion can be carried forward, for if what goes on during episodes of thinking with images is just the sort of thing that goes on when imagery is not being used, then the postulation of a special image system would be redundant and gratuitous, *regardless of whether we have a worked-out theory of any kind of reasoning*. The default assumption, the one that we should follow in the absence of evidence to the contrary, is that thinking involves only one kind of mechanism and form of representation. While this may very well not be true, the burden of proof must fall on those who postulate a particular special property of the image system. That's why I refer to this assumption as the "null hypothesis."

This framework should be uncontroversial as a basis for setting out the investigation of mental imagery. It turns out that even within this framework, the empirical investigation of these questions is much more difficult than might appear. A number of distinctions must first be made, as I suggested above. In particular we need to distinguish between explicit and tacit knowledge and between patterns of reasoning that arise from habit or preference, as opposed to patterns that arise because of the nature of the fixed mechanisms involved, and between patterns that are intrinsic to reasoning with images as opposed to those that would arise no matter what form or modality of reasoning was being used. Even if we do find that there are properties intrinsic to reasoning with images, we must still ask whether these arise because of certain imagery-specific forms of representation or processing that are being deployed or, as generally claimed, because imagery involves the use of specifically *visual* mechanisms.

6.2 Content, form and substance of representations

One thing that everyone agrees on is that mental images are *representations*: they encode information about the world, primarily, though not exclusively, the visible world. When we speak of a representation there are at least three levels about which we can theorize⁵⁰ (for a detailed discussion of these "levels" see Pylyshyn, 1984a). At the *first* level, we can inquire about the *form* of the representation, the system of codes by which mental objects can represent aspects of the world. These codes need not be discrete symbols, but they do have to embody some principles by which they combine and in virtue of which they are able to represent novel things – they need to form a productive system (see Fodor & Pylyshyn, 1988). In the case of language, these principles are referred to as the *syntax* of the language. Differences in representational content (in what the linguistic objects represent) are attributed, at least in part, to the syntactic structure of the representation. At the *second* level we can ask about the content, or what the representation *represents*, or what it is about. The thing represented need not even exist (e.g., we can represent unicorns with no difficulty) nor, if it does exist, is the content of the representation the same as the thing being represented. It's not only which particular thing is represented that constitutes the content of the representation, but the category under which it is represented or what it is represented *as*. If we represent a certain physical thing as Dr. Jeckyl our representation has a different content than if we represent the very same physical thing as Mr. Hyde. If we represent a certain point of light as the planet Venus, the representation has a different content than if we represent it as the morning star or as the evening star, even though all these representations refer to the very same physical body. The difference in how it is

⁵⁰ (Newell, 1980b) refers to these levels as the symbol level, the knowledge level, and the physical level, respectively. He also mentions additional levels that are important in actual digital computers (e.g., the register transfer level). There may, in fact, be reason to include other levels in the case of mental processes (e.g., an abstract neurological level that accounts for additional generalizations) but as far as I am aware none has been proposed so far.

represented (or what it is represented as) has real consequences for potential behavior. A great deal has been said about the notion of content in philosophy, but for our purpose all we need to acknowledge is that there is more to being a representation than having a certain form. For many purposes we also need to talk about the content of the representation. But we need to distinguish between properties of the representation's form and properties of the representation's content.

The *third* facet of a representation is how it is realized or implemented. Here too we need to take care since we can ask about how it is realized in at least two senses or at two different levels of abstraction. We can ask how a particular brain realizes a particular individual (token) representation at a particular instant in time. Or we can ask the more general question of what properties must the representational medium or the mechanisms for manipulating the representations have in order to account for certain empirical facts, regardless of how the representation is physically or biologically realized. At this level of abstraction we are not concerned precisely with how the instantiation and operations over representations occurs in the brain of person A or in the brain of person B, or in the brain of an animal, or even in the hardware of a computer. One of the discoveries of the last 40 or so years of information processing psychology (now transformed into Cognitive Science) is that it is possible to ask the question: *How is it done?* without requesting an answer in terms of biology or physics. To ask how it is done in this more abstract sense is to ask how it is realized by information processing resources (mechanisms, forms of encoding, types of memory, and so on) that occur in what we call the *cognitive architecture*. The cognitive architecture is just a more abstract description of the way the brain or computer functions in relation to its representing capacity, but it is a level of description that captures the essential aspect of information processing abstracted away from the sorts of details that differ from occasion to occasion and from person to person.

Elsewhere I have written extensively on the topic of cognitive architecture (Pylyshyn, 1984a; Pylyshyn, 1991a, 1996) and I will not repeat it here. I wish only to point out that such issues arise in the present context because the different types of explanatory principles or levels are often confused in discussions about mental imagery. For example, we have already seen how mental images are often discussed as having a certain form or having certain special properties, when what is meant is that the *content* of images (or the things referred to or depicted in the images) have these properties. The property of being larger or smaller or been further or closer are among such properties. There is clearly a difference between claiming that you have an image of something big (or red or heavy or slow or ...) and claiming that the image itself is big (or red or heavy or slow or ...). While there is general agreement that we need all three levels of description when we discuss systems of representation it has not always been the case that these levels have been kept distinct. In particular, when one claims certain properties for images it is important that we be clear as to the level to which our claims apply. In Chapter 7 we will see that it is especially true when we consider claims such as that images *have* or *preserve* metrical or spatial properties of the world they represent.

6.3 What is responsible for the pattern of results obtained in imagery studies?

6.3.1 Cognitive architecture or tacit knowledge

The distinction between effects attributable to the intrinsic nature of mental mechanisms and those attributable to more transitory states, such as people's beliefs, utilities, long-standing habits, or interpretation of the task at hand, is central, not only to understanding the nature of mental imagery, but to understanding mental processes in general. The former sorts of effects invoke what has been called the cognitive architecture (Fodor & Pylyshyn, 1988; Newell, 1990; Pylyshyn, 1980, 1984a; Pylyshyn, 1991a, 1996); one of the most important ideas in cognitive science. It refers to the set of properties of mind that are fixed with respect to certain kinds of influences. In particular, the cognitive architecture is, by definition, not directly altered by changes in knowledge, goals, utilities nor any other representations (e.g., fears, hopes, fantasies, etc). In other words when you find out new things or when you draw inferences from what you know or when you decide something, your cognitive architecture does not change. Of course, if as a result of your state of beliefs and desires you decide to take drugs or to change your diet or even to repeat some act over

and over, this can result in changes to your cognitive architecture, but such changes are not a direct result of the changes in your cognitive state. A detailed technical exposition of the distinction between effects attributable to knowledge or other cognitive states and those attributable to the nature of cognitive architecture are beyond the scope of this article (although this distinction is the subject of extensive discussion in Pylyshyn, 1984a, Chapter 7). This informal characterization and the following example will have to do for present purposes.

To make this point in a more concrete way, I invented a somewhat frivolous but revealing example involving a certain mystery box of unknown construction whose pattern of behavior is known (Pylyshyn, 1984). This box is known to emit long and short pulses according to the principle that pairs of short pulses usually precede single short pulses, except when a pair of long-short pulses occurs first. In this example it turns out that the observed regularity (shown in Figure 6-1), though completely regular when the box is in its “ecological niche,” is not due to the nature of the box (to how it is constructed) but to an entirely extrinsic reason. The two sorts of “reasons” for the observed behavior (intrinsic or extrinsic) are analogous to the architecture versus tacit knowledge distinction and is crucial to understanding why the box works the way it does, as well as to why certain patterns of cognition occur.

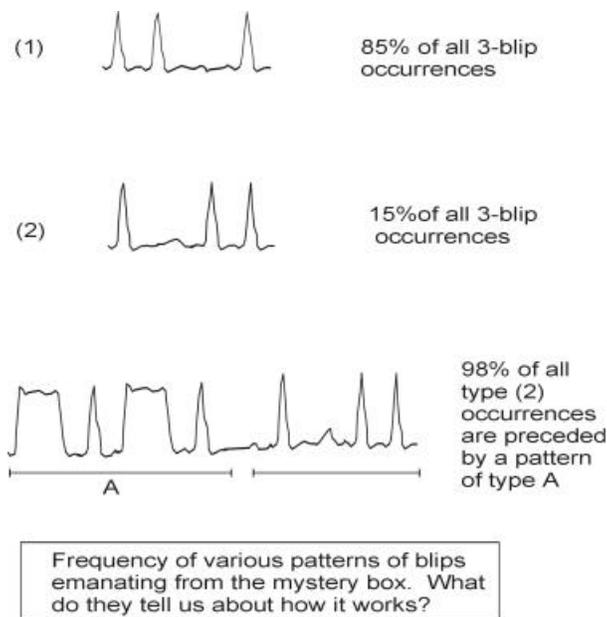


Figure 6-1. Pattern of blips observed from a box in its typical mode of operation. The question is: Why does it exhibit this pattern of behavior? What does this behavior tell us about how it works?

The reason why this particular pattern of behavior occurs in this case can only be appreciated if we know that the pulses are codes, and the pattern is due to a regularity in *what they represent*, in particular that the pulses represent English words spelled out in International Morse Code. The observed pattern does not reflect how the box is wired or its functional architecture – it is due entirely to a regularity in the way English words are spelled (the principle being that generally *i* comes before *e* except after *c*). Similarly, I have argued that in the image scanning case the pattern reflects a principle that the subjects believe holds in the imagined world, and not a principle of their mental architecture: The pattern arises from the fact that subjects know what happens when you scan a picture with your eyes and they make the same thing happen in their imagined simulation. The reason that the behavior of both the mystery code box and the cognitive system do not reveal properties of its intrinsic nature (technically, of its *architecture*) is that both are capable of quite different regularities if the world they were representing behaved differently. They would not have to change their nature (their “wiring” or their causal structure) in order to change their behavior. The way the behavior can be altered provides the key to how you can tell what is responsible for the observed

regularity. This is the basis for the methodological criterion called “cognitive penetrability” described in section 6.3.3.

Clearly it is important to distinguish between architectural and knowledge-based explanations in understanding mental imagery. I noted earlier that in order to understand what goes on in mental imagery it is essential to distinguish the case in which people are merely making their phenomenal image (*whatever* that turns out to correspond to in our theory) do what they independently believe would happen in certain situations, from the case where it is the very fact of putting their thoughts in the form of a mental image – and thus being constrained by the properties of mental images – that is responsible for the outcome. In the second case the claim is that it is properties intrinsic to images, to their form or their particular realization in the brain, that results in thoughts unfolding the way they do. In other words, in this second case we are claiming that the observed properties of the image-based thoughts are a direct consequence of properties of the special cognitive architecture used in mental imagery. In the first case (the one in which people simply make their image do what they believe would happen) the properties of the image are irrelevant to explaining the way the thoughts unfold: nothing is gained by postulating that an image has certain properties since these properties do not figure in any explanation. In that case, saying that an image is like a picture may reflect the phenomenology of imagery, yet is theoretically irrelevant to explaining the outcome of imaginal thinking. Thus the phenomenology-based theory of what the image is like does no work because the real explanation lies elsewhere, for example it may lie in what people put into their phenomenal image or what they made it do.

To see that the distinction between knowledge-based and mechanism-based accounts of why things work they way they do really does make a difference, try to imagine a physical situation whose operating principle is unknown to you. For example, imagine that you have a jar filled with sugar and a jar filled with water. Imagine, in your mind’s eye, that the water is slowly poured into the jar of sugar, as shown in Figure 6-2. Does the water in the sugar-filled jar begin to overflow – and if so at what point in the pouring does it do so? In this case it seems clear that what will happen in your imagination will depend on what you know (or believe) would happen in the world, if you were to observe such an experiment being performed. Your imagination does not have built into it the subtle principles by which solids dissolve in fluids, which involves understanding how molecules of certain solids can take up the spaces between molecules of the fluid. What happens in your imagination is just exactly what you *think* would happen (perhaps based on what you once saw happen), nothing more. Someone who claimed that it was up to their image to determine what will happen and that it was the properties of their imagery system that generated the result, would be letting their phenomenal experience cloud their judgment. To see that this must be so, try making your image do something different by just willing it to!



Figure 6-2 Imagine pouring water into a beaker full of sugar. Does it eventually overflow?

Take another example not involving such an obscure principle of physics. You are asked what color you get if you look through a yellow filter superimposed on a blue filter. The way that many of us would go about solving this problem, if we did not know the answer as a memorized fact, is to “imagine” a yellow filter and a blue filter being superimposed. We generally use the “imagine” strategy when we want to solve a problem about how certain things would look. So imagine looking at a white wall through a blue filter and a yellow filter while you bring them into overlapping positions, as illustrated (without the benefit of color) in Figure 6-3. What color do you see at the overlap? More important, ask yourself why do you see *that*

color in your mind's eye rather than some other color? Some people (e.g., Kosslyn, 1981) have argued that the color you see follows from a property of the imagery "medium", of how colors are encoded and displayed in images. But since there can be no doubt that you can make the color of the overlap portion of the filters be *any* color you wish, it can't be that the image format or the architecture involved in representing colors is responsible. What else can it be? This is where the notion of *tacit knowledge* plays an important role in cognitive science (Fodor, 1968, see also section 6.3.3). It seems clear in this case that the color you "see" depends on your tacit knowledge either of principles of color mixing or of these particular color combinations (having seen something like them in the past). In fact people who do not know about *subtractive* color mixing generally get the above example wrong (mixing yellow light with blue light in equal amounts produces white light, but overlapping yellow and blue filters leads to green light being transmitted).

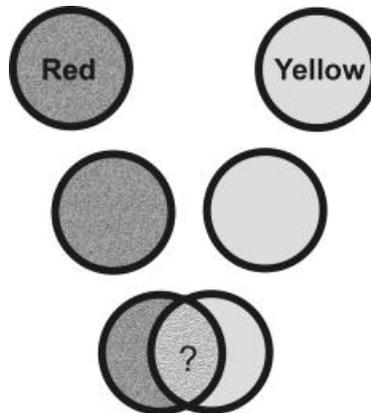


Figure 6-3. Imagine the red and yellow disks moving closer and closer until they overlap. What color do you see in your image where the two disks overlap?

When asked to do this exercise, some people simply report that they see no color at the intersection, or a washed-out indefinite color. Still others claim that they "see" a color different from the one they report when asked to answer without imagining the filter scenario (reported in Kosslyn, 1981). Cases such as the latter have made people skeptical of the tacit knowledge explanation. There are indeed many cases where people report a different result when using mental imagery than when asked merely to answer the question without using their image. Yet it is a general property of reasoning that the way the question is put and the reasoning path used to get to the answer can affect the outcome. As I will suggest in section 6.3.2.3, knowledge can be organized in many different ways and it can be accessed in equally many different ways – or not accessed at all if it seems like more work that it is worth. For example, consider the following analog of the color-mixing task. Imagine a teacher writing the following on a blackboard: "759 + 356 = ___?". Now, as quickly as you can, without stopping to think about it, imagine that the teacher continues writing on the board. What number can you "see" the teacher write in the blank? Now ask yourself why you saw *that* number rather than some other number being written in the blank. People may give different answers depending on whether they believe that they are supposed to work it out or whether in the interest of speed they should guess or merely say whatever comes to mind. Each of these is a *different task*. Even without a theory of what is special about visual imagery, we know that the task of saying what something would look like can be (though it needn't be) a different task from the task of solving a certain intellectual puzzle about colors, as you can see if you consider the difference between the two corresponding ways of filling the blank in the arithmetic example. It can be as different as the difference between free-associating to a word and giving its definition. The task of imagining something unfolding in your "mind's eye" is a special task: It's the task of simulating as many aspects of the visual situation as possible, as many aspects as you can – *because this is what it means to "imagine X happening."*

In most of the cases studied in imagery research, it would be odd if the results did not come out the way picture theories would predict, and if they did, the obvious explanation would be that subjects either did not

know how things would work in reality or else they misunderstood the instructions to “imagine x”. For example if you were asked to construct a vivid and detailed image of an excellent performance of the Minute Waltz, played on a piano right in front of you, the failure of the imagined event to take approximately one minute would simply confirm that you had not carried out the task well (or at all). Taking roughly one minute is inherent in a real performance and thus it is natural to assume it to be indicative of a good imagined re-creation or simulation of such a performance. To realistically imagine a musical performance of a piece *means* to imagine (i.e., think of) each token note being played in the right order and at the right loudness and duration, whether or not it involves any sensory qualities being “perceived” by the “mind’s ear,” i.e., whether or not it is accompanied by a particular conscious experience.

Finally, let me reiterate what kind of tacit knowledge is relevant to this discussion, because there has been serious misunderstanding of this question. The only knowledge that is relevant to the tacit knowledge explanation is knowledge of *what things would look like* in certain situations, in particular in situations like the ones in which they are to imagine themselves. Thus it is not a criticism of this type of explanation to point out, (e.g., Farah, 1988, pp 314-315), that people are unlikely to know how their visual system or the visual brain works. That’s not the tacit knowledge that is relevant. Nor is it the tacit knowledge of what results the experimenter expects (sometimes referred to as “experimenter demand effects”) as many have assumed (Finke & Kurtzman, 1981b). Of course, the latter is relevant as well, and may even explain many of the findings in imagery studies (as suggested by Banks, 1981; Intons-Peterson, 1983; Intons-Peterson & White, 1981; Mitchell & Richman, 1980; Reed, Hock & Lockhead, 1983; Richman, Mitchell & Reznick, 1979), but it is not what I mean by the tacit knowledge explanation. All I mean is that subjects in studies where they are asked to “imagine X” use their knowledge of what “seeing X” would be like to simulate as many of these effects as they can. This, of course, depends on people having certain psychophysical skills, such as the ability to generate time intervals proportional to certain computed magnitudes (Fraisse, 1963), or to compute the time-to-collision of moving objects (see section 6.5.3).

6.3.2 Problem-solving by “mental simulation”: Some additional examples

The idea that what happens in certain kinds of problem solving can be viewed as off-line *simulation* has had a recent history in connection not only with mental imagery (Currie, 1995), but also with other sorts of problems in cognitive science (Klein & Crandall, 1995). Take, for example, the question of how we manage (rather successfully) to predict other people’s behavior in everyday life. One proposal, referred to as the “off-line simulation” view, argues that we do not need to assume that people have a tacit theory of how other people’s minds work. Instead all we need to assume in order to predict what they will do is to put ourselves in their position and ask what *we* would do. This way of putting it still leaves open the question of whether the latter predictions come from a special behavior-generating mechanism or from a tacit theory, and the difference is hotly debated in the case of social cognition (the arguments are reviewed in Nichols, Stich, Leslie, & Klein, 1996).

Granted that the “simulation mode” of reasoning is used in various sorts of problem solving, two questions still remain: (1) Why should this mode be used at all, as opposed to some more direct way of solving the problem, and (2) When it is used, what does the real work of solving the problem – a special image mechanism or inferences from tacit knowledge? I have already suggested one major reason why subjects might use the simulation mode in imagery studies: The experimental design invites it inasmuch as the request to “imagine X” is properly understood as a request to pretend that you are looking at situation X unfolding and report what you would see. Even without instructions from an experimenter, the simulation mode is often natural because of the nature of the task – e.g., if it is a task that you would normally carry out by doing something and observing what happens you might be tempted to imagine doing the same thing. Imagery is most often used in conjunction with tasks that ask what would happen in a counterfactual (what if...?) situation involving perceivable spatio-temporal events.

In what follows I will sketch a number of extremely influential experimental results and compare explanations given in terms of inherent properties of the image (the architecture of the image system) and those given in terms of the simulation-from-tacit-knowledge explanation (and other considerations as well).

6.3.2.1 Scanning mental images

Probably the most cited result in the entire repertoire of research motivated by the picture-theory is the image-scanning phenomenon. Not only has this experimental paradigm been used dozens of times, but various arguments about the metrical or spatial nature of mental images, as well as arguments about such properties of the mind's eye as its "visual angle" rest on this phenomenon. Indeed, it has been referred to as a "window on the mind" (Denis & Kosslyn, 1999).

It has been shown that it takes longer to "see" a feature in a mental image the further away it is from a place where one has been focusing. So for example, if you are asked to imagine a dog and inspect its nose and then to "see" what its tail looks like it will take you longer than if you were asked to first inspect its hind legs. Here is an actual experiment reported in (Kosslyn, Ball & Reiser, 1978). Subjects were asked to memorize a map such as the one in Figure 6-4. They are then asked to imagine the map and to focus their attention on one place – say the "church". In a typical experiment (there are many variants of this basic study) the experimenter says the name of a second place (say, "beach" or "tree") and subjects are asked to examine their image and to press a button as soon as they can "see" the second named place on their image of the map. What Kosslyn (and many others) found is that the further away the second place is from the place on which subjects are initially focused, the longer it takes to "see" the second place in their "mind's eye". From this result most researchers have concluded that greater distances on the imagined map are represented by greater distances in some (mental) space. In other words, the conclusion is that mental images have spatial properties – i.e., they have spatial magnitudes or distances. This is a strong conclusion about cognitive architecture. It says, in effect, that the symbolic code idea I discussed earlier does not apply to mental images. In a symbolic encoding two places can be represented as being further away just the way we do it in language; by saying the places are n meters from one another. But the representation of larger distances is not itself in any sense larger. The question then is: Is this conclusion about architecture warranted? Does the difference in time in this case reveal a property of the architecture or a property of what is represented? This exactly parallels the situation in the color-mixing example I discussed earlier where I asked whether a particular regularity revealed a property of the architecture or a property of what people know or believe – a property of the represented situation of which they have tacit knowledge. To answer this question we need to determine whether the pattern of increasing scanning time arises from a fixed capacity of the image-encoding or image-examining system, or whether the time it takes can be changed by changing the task or the beliefs people hold about how things are in the world; whether it is cognitively penetrable.

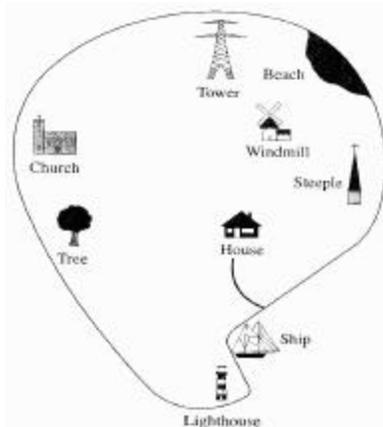


Figure 6-4: Example of a map to be learned and then imaged in one's "mind's eye" to study mental scanning

This is a question to be settled in the usual way – by careful analyses and experiments. But even before we do the experiment there is reason to suspect that the time-course of scanning is not a property of the

cognitive architecture. Do the following test on yourself. Imagine that there are lights at each of the places on your mental image of the map. Imagine that a light goes on at, say, the beach. Now imagine that this light goes off and one comes on at the lighthouse. Did you need to scan your attention across the image to see this happen – to see the light come in at the lighthouse? Liam Bannon and I repeated the scanning experiment (see the description in Pylyshyn, 1981) by showing subjects a real map with lights at the target locations, much as I just described. We allowed the subjects to turn lights on and off. Whenever a light was turned on at one location it was simultaneously extinguished at another location. Then we asked subjects to imagine the map and to indicate (by pressing a button) when a light was on and they could “see” the illuminated place in their image. The time between button presses was recorded and its correlation to the distances between illuminated places on the map was computed. We found that there was no relation between distance on the imagined map and time. You might think: Of course there was no time increase with increasing distance because subjects were not asked to imagine scanning that distance. But that’s just the point: You can imagine scanning over the imagined map if you want to, or you can imagine just hopping from place to place on the imaginary map. If you imagine scanning, you can imagine scanning fast or slow, at a constant speed or at some variable speed, or scanning part way and then turning back or circling around! You can, in fact, do whatever you wish since it is your image and your imagining.⁵¹ At least you can do these things to the extent that you can create the phenomenology or the experience of them and providing you are able to generate the relevant measurements, such as the time you estimate it would take to get from point to point.

The proposal is that the task of imagining invites observers to pretend (in whatever way they can) that they are looking at some situation – that’s what “imagine that…” means. The criticism of the scanning studies is not that the investigators have failed to control for something and have allowed an artifact to contaminate the results. It is that a proper understanding of the task requires that they try to do certain things; that is what is meant by a “task demand”. Other investigators have confirmed the relevance of task demands (Intons-Peterson, 1983; Intons-Peterson & White, 1981; Mitchell & Richman, 1980; Reed et al., 1983; Richman et al., 1979). Yet when these criticisms are discussed in the literature, they are often understood as the criticism that the results are due to the experimenter leading the subject, or that subjects were complying with the experimenter’s expectations. While this may often be true, the deeper point is that subjects are mostly just doing the task, as they understand it – i.e., pretending that they are looking at a map and seeing places on it.

Notice that whether or not you choose to simulate a certain temporal pattern of events in the course of answering a question may also depend in part on whether simulating that particular pattern seems to be relevant to the task. It is not difficult to set up an experimental situation in which simulating the actual scanning from place to place does not appear so relevant to solving a particular problem. For example, we ran the following experiment involving extracting information from an image (Pylyshyn, 1981). Subjects were asked to memorize a map and to refer to their image of the map in solving the problem. Rather than asking them to imagine looking at one place on the map and then to look for a second named place and indicate when they could “see” it (as in the original studies by Kosslyn et al., 1978), the task was to indicate the compass direction from the second named place to the previously focused place. This direction-judgment task requires that the subject make a judgment from the perspective of the second place, so if anything requires focusing at the second place on the map this was certainly a good candidate. Yet in this experiment, the question of how you get from the first place to the second place on the map was far less prominent than it was in the “tell me when you can see X” task. The present task required that subjects concentrate on the relative directions between two places once both places had been retrieved, rather than

⁵¹ When we first carried out these studies we were (quite rightly, in my view) criticized on the grounds that it was obvious that you did not have to scan your image if you did not want to, and if you did you could do so according to whatever temporal pattern you chose. It still seems to me that the studies we did (including the one described below) only demonstrate the obvious. That being the case one might well wonder what the fuss is about over the scanning phenomenon (as well as the image size phenomenon describe below), why dozens of studies have been done on it and why it is interpreted as showing *anything* about the nature of mind as opposed to choices that subjects make.

on how they got from one place to the next or on how far away the two places were on the map. In this case we found that the distance between places had no effect on the time taken to answer the question. It seems that the effect of distance on reaction time is cognitively penetrable.

People have sometimes suggested that one can accommodate the finding that the “scanning effect” is cognitively penetrable by noting that the observed phenomenon depends on both the form of the image and the particular processes that use it, so that the differences in the process in this case can account for the different result one gets in different contexts. This is true; but then what explanatory work is being done by the alleged imagery medium and its claimed spatiality? If we can appeal to the nature of the process, then the hypothesized properties of the image play no role in the explanation. So long as the assumption that there is a depictive representation that “preserves metrical distance” plays no role in the explanation, and does not add any constraints on possible behavior, it remains theoretically irrelevant.

Not can observers move their attention from one imagined object to another without scanning continuously through the space between them, but we have reason to believe that they actually *cannot* move their attention continuously as though smoothly tracking an imagined movement. In interviewing subjects after the study, many said that they did not feel they moved or scanned their attention *smoothly* through intermediate locations. They claimed that they did not notice (or “see”) objects at intermediate locations in their mental image in the course of their scanning, unless the objects were relevant to the task. This got us wondering whether it was even possible to continuously scan an image as required by Kosslyn’s display-scanning model. The model claims that in getting from A to B on a mental image you must trace a path that takes you through all intermediate points (within the resolution of the image), just as a moving spot or a smooth eye movement would visit such places in the corresponding case of a real map. Without this assumption there would be no reason to predict that the time it takes to scan a certain distance should be proportional to the distance. But both introspection and objective studies suggest that we are unable to actually *move* an imagined point through a smooth set of invisible places along a mental scan path. In fact (Pylyshyn & Cohen, 1999) carried out a number of experiments which show that observers are poor at judging where an imagined moving object is located at various times during its imagined passage through a region where there are no visible elements (e.g., in the dark). This suggests that the imagined object does not actually *pass through* a sequence of locations, a view defended later in section 6.5.3.

Given that the times for mental scanning are actually computed, as opposed to observed, one might well wonder why people bother to imagine a point of focus being scanned (even if not continuously) across their image? In the case of scanning while looking at a scene, I have already suggested that this might pay off because it allows people to use their superbly accurate capacity to compute “time to collision” based on a given speed of movement and a give (perceived) collision location. But it has been reported that people appear to use the scanning strategy even when not observing a scene (e.g., with their eyes closed). Why should they persist on using this method when scanning entirely in their imagination, so that the visual time-to-collision computation may not be available (although it may actually be available from memory – people can compute time-to-collision after a moving objects, such as a baseball, disappears behind an occluding surface)? Assuming that people actually do use the mental scanning simulation with their eyes closed, a possible reason, already alluded to earlier, is that when using the simulation mode to imagine solving a problem, people may carry over strategies that they use in real situations, where the strategy is clearly the appropriate one. Consider the example presented by (Pinker et al., 1984), in which people claim they “extrapolate” a line with an arrow, whose location and direction is taken from memory, in order to determine whether the arrow points at a particular dot in a recalled image. In this task, extrapolating the line from the arrow is clearly the right strategy *if you have ruler and pencil and paper* since in that case you would be able to see whether the extrapolated line would intersect the dot. It may also be the right strategy when the image is superimposed on a viewed scene (as was the case in the earlier experiment by Finke & Pinker, 1982), since in that situation subjects can use both their ability to index features in the display and also use their time-to-collision computation. So in the purely imagined case the problem for the theorist is not to explain why that strategy was used (it was used because it would have been the appropriate thing to do in the situation being imagined), but rather to explain how such a strategy could possibly work without a real display. Drawing a mental line in mental space cannot solve the problem because “mental” lines do not

actually *have* the property that when they are extrapolated they intersect appropriately situated mental objects. In order to imagine the line being drawn you don't actually have to draw anything, all you have to do is *imagine that* (i.e. think the thought that) the line is initially short and gets progressively longer. And you don't need a special form of representation to think the thought that there is a line having such-and-such a length, nor do you need a special form of representation to think that the line is getting longer. All you need is a representational system capable of representing (not of *having*) distances. But of course so long as there is no physical line on a physical surface, no perceptual judgments can be based on such thoughts. The judgments are made by some other means, which, as usual in such cases, are not available to introspection.

6.3.2.2 *The "size" of mental images*

Here is another example of a widely cited result that might well be attributed to the use of tacit knowledge to simulate the imagined event. Consider the finding that it takes more time to report some visual detail of an imagined object if the object is imagined to be small than if it is imagined to be large (e.g., it takes longer to report that a mouse has whiskers if the mouse is imagined as tiny than if it is imagined as huge). This seems a clear candidate for what I have referred to as a result of an implied requirement of the imagery task. For if you are asked to imagine something small then you are likely to imagine it as having fewer visible details than if you are asked to imagine it looming large directly in front of you, *whatever* sort of representation that involves. One reason you might do this is because when you actually *see* a small object (or an object that is far away) you can make out fewer of its details due to the limited resolution of your eye. If you are to accurately simulate the visual experience of seeing an object, then in the case of a small object you have to perform some additional operation to make the details available (e.g. imagine bringing the object closer or zooming in on it). But what does it mean to make your image "larger"? Such a notion is obviously meaningful only if the image *has* a real size or scale. If, as in our null hypothesis, it is like a description, then size has no literal meaning. You can *think of* something as large or small, but that does not make some *thing* large or small. On the other hand, *which details are represented* in your imagination does have a literal meaning: You can put more or less detail into your active representation. So if this is what the task demands when the mouse is imagined as "large" then the result is predictable without any notion of real scale applying to the image.

The obvious test of this proposal is to apply the criterion of cognitive penetrability. Are there instructions that can ameliorate the effect of the "image size" manipulation, making details easier to report in small images than in large ones and vice versa? Can you imagine a small but extremely high resolution and detailed view of an object, in contrast to a large but low-resolution view or a view that for some reason lacks details? Surely you can, though I know of no one who has bothered to carry out an experiment such as asking subjects to report details from a large blurry image versus a small clear one. What if such an experiment were done and showed that it takes longer to report details of a large blurry object than a small clear one? Would this show that it is the presence of visible details rather than size that is the relevant determiner of response time? Surely we expect that examining a blurry object will lead to difficulty in reporting its fine-grained properties. Think about what it would mean if you were faster at reporting details from a blurred image or faster in reporting details from a small image. The strangeness of such a possibility should alert us to the fact that what is going wrong lies in what it *means* to have a small versus a large mental image, or a blurred versus a clear image. Such results would be incompatible with what happens in *seeing*. If one failed to see fine details in a large object there would have to be a reason for it, such as that you were seeing it through a fog or out of focus or on a noisy TV, and so on. As long as examining a visual image *means* simulating what it is like to see something, this will necessarily be the case. If that is so then how could studies of mental image inspection fail to show that it parallels the case of seeing, assuming that observers know more-or-less what it would be like to see the object that is being imagined? This goes for any property of seeing of which observers have some tacit knowledge or recollection. Thus it applies to the findings concerning the acuity map of vision, which appears to be roughly duplicated in the acuity map of mental imagery (Finke & Kosslyn, 1980). As noted earlier, observers do not need to have articulate scientific knowledge of visual acuity; all they need is to remember roughly how far into the periphery of their visual field things can be before they cease to be resolvable, and it is not surprising that this is easier to

do while turning your head and pretending to be looking at objects in your periphery. This simply illustrates the well-known phenomenon that recall is better when the recollection takes place in an environment similar to the one that obtained in the situation being recalled.



Figure 6-5. The point of this cartoon is self-explanatory: We must not confuse the content of representations with their intrinsic property. (S. Harris, from *American Scientist*, 66, 647)

6.3.2.3 Mental “paper folding”

These thus seems to be reason to think that many of the mental imagery results may be due to subjects simulating what they think would happen if they witnessed the imagined event taking place. But why should people go through the trouble of simulating a situation if they already known (albeit tacitly) what the answer is? There are many reasons why one might use a “simulation mode” in answering a question. One major reason has already been considered: The task itself invites it since “imagine X” means “imagine that you are seeing X.” But there are other reasons as well, some having to do with how the relevant tacit knowledge is organized. For example, to answer the question: What is the fourth (or n 'th) letter in the alphabet after “M,” people normally have to go through the alphabetical sequence (and it takes them longer the larger the value of n). Similarly, the findings reported by (Shepard & Feng, 1972) are easily understood if one takes into account how knowledge is organized. In their experiment, subjects are asked to mentally fold pieces of paper, such as shown in Figure 6-6, and to report whether the arrows marked on the paper would touch one another. Try this yourself. You will find, as they did, that the more folds it would require to actually fold the paper and see whether the arrows coincide, the longer it takes. Shepard & Feng took this to indicate that working with images parallels working with real objects. Elsewhere (Shepard & Chipman, 1970) call this principle “second order isomorphism” and claim that it is a general property of mental images (though I have argued that such a principle is true of any empirically adequate functional model, regardless of the form of representation used Pylyshyn, 1984a, p 203).

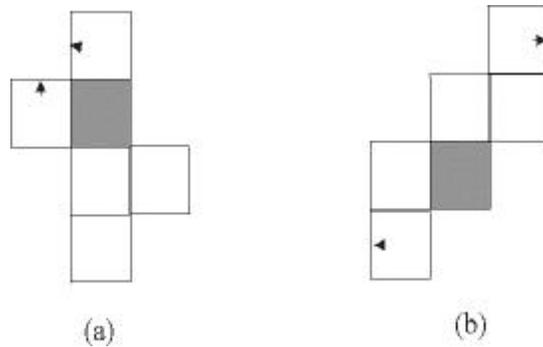


Figure 6-6: Two of the figures used in the (Shepard & Feng, 1972) experiment. The task is to imagine folding the paper (using the dark shaded square as the base) and say whether the arrows in these two figures coincide. The time it takes increases with the number of folds required.

The question we need to ask about this task is the same as the question we asked in the case of the color mixing task: What is responsible for the relation between time taken to answer the question and the number of folds it would have taken by folding real paper? This time the answer is not simply that it depends on tacit knowledge, because in this case it is not just the content of the tacit knowledge that makes the difference. That in itself would explain how it is possible for a subject to imagine folding the paper. After all, if you are asked to imagine folding paper then you are required (on pain of failing to follow the instructions) to imagine each step the folding goes through. But in this case one would presumably get the same result even if one did not ask the subject to imagine folding the paper. Still, it is hard to see how to answer to this question without imagining going through the sequence of folds. Why should this be so? A plausible explanation that does not appeal to properties of a special imagery system, is that the reason has to do with how knowledge of the effect of folding is organized – just as was the case in our earlier alphabet example. What we know by rote about the effects of paper folding is just this: *we know what happens when we make one fold*. Consequently to determine what would happen in a task that (in the real world) would require 4 folds, we have to apply our one-fold-at-a-time knowledge four times. Recall the parallel case with letters: In order to say what the fourth letter after M is we have to apply the “next letter” rote knowledge four times. In both the alphabet case and the paper folding case a person could easily memorize the results of macro-operations. They could commit to memory such facts as what results from double folds of different types; or which letter of the alphabet is two (or n) letters after a given letter. If that were how knowledge was organized the results discussed above would most likely no longer hold. The important point is that once again the experimental result tells us nothing about how the states of the problem are represented – or about any special properties of image representations. They tell us only what knowledge the person has and how it is organized.

The role played by the structure of knowledge is ubiquitous and may account for another common observation about the use of mental imagery in recall. We know that some things are easier to recall than others and that it is easier to recall some things when the recall is preceded by the recall of other things. Knowledge is linked in various intricate ways. In order to recall what you did on a certain day it helps to first recall what season that was, what day of the week it was, where you were at the time, and so on. (Sheingold & Tenney, 1982; Squire & Slater, 1975) and others have shown that one’s recall of distant events is far better than one generally believes because once the process of retrieval begins it provides clues for subsequent recollections. The reason for bringing up this fact about recall is that such sequential dependencies are often cited as evidence for the special nature of imagery (Bower, 1976; Paivio, 1971). Thus, for example, in order to determine how many windows are there in your home, you probably need to imagine each room in turn and look around to see where the windows are, counting them as you go. In order to recall whether someone you know has a beard (or glasses or red hair) you may have to first recall what they look like (i.e., recall an image of them). Apart from the phenomenology of recalling an appearance, what is going on is absolutely general to every form of memory retrieval. Memory access is an ill understood process, but at least it is known that it has sequential dependencies and other sorts of access

paths and that these paths are often dependant on spatial arrangements (which is why the “method of loci” works well as a mnemonic device).

6.3.2.4 Mental Rotation

One of the earliest and most cited results in the research on the manipulation of mental images is the “mental rotation” finding. (Shepard & Metzler, 1971) showed subjects pairs of drawings of three-dimensional figures, such as those illustrated in Figure 6-7, and asked them to judge whether the two objects depicted in the drawings were identical, except for orientation. Half the cases were mirror-images of one another (or the 3D equivalent, called enantiomorphs), and therefore could not be brought into correspondence by a rotation. Shepard and Metzler found that the time it took to make the judgment was a linear function of the angular displacement between the pair of objects depicted (except when the angle was over 180 degrees, when in some cases the time it took became proportional to the angular distance remaining – i.e., to the angle measured counterclockwise).

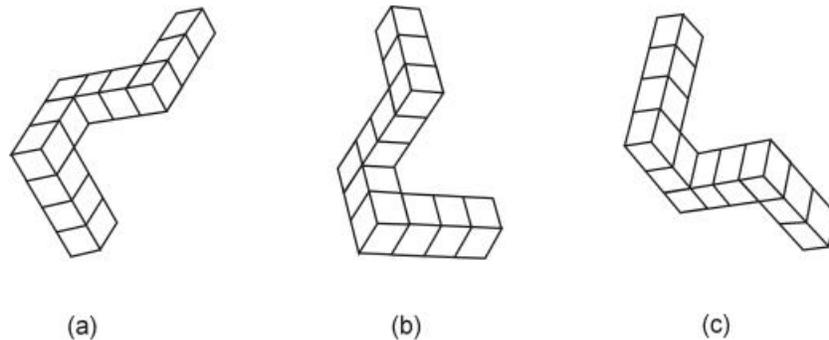


Figure 6-7. Examples similar to those used by (Shepard & Metzler, 1971) to show “mental rotation.” The time it takes to decide whether two figures are identical except for rotation, as in the pair (a → b) or are mirror images, as in the pair (a → c) increases linearly as the angle between them increases.

This result has been universally interpreted as showing that images are “rotated” continuously and at constant speed in the mind and that this is, in fact, the means by which the comparison is made: We rotate one of the pair of figures until the two are sufficiently in alignment that it is possible to see whether they are the same or different. The phenomenology of the Shepard and Metzler task is clearly that we rotate the figure in making the comparison. I do not question either the phenomenology nor the description that what goes on in this task is “mental rotation.” But there is some question about what these results tell us about the nature of mental images. The important question is not whether we can or do imagine rotating a figure, but whether we solve the problem by means of the mental rotation. For mental rotation to be mechanism by which the solution is arrived at, its utility would have to depend on some intrinsic property of images. For example it might be the case that during mental rotation the figure moves *as a rigid form* through a continuum of angles, thus capitalizing in an intrinsic property of the image format. Also relevant to this explanation is the question of whether we are *required* to apply this particular transformation in order to compare two shapes in different orientations. Not surprisingly, it turns out to be important that the mismatches be ones in which the figures have the same features but are enantiomorphic images, otherwise observers simply look for distinguishing features and no mental rotation ensues (Hochberg & Gellman, 1977). There are two points to be made about this mental rotation phenomenon.

First, contrary to the general assumption, the figural “rotation” could not be a holistic process that operates on an entire figure, changing its orientation continuously while rigidly retaining its rigid. In the original 3D rotation study (Shepard & Metzler, 1971), the two comparison figures were displayed at the same time. A record of eye movements made while doing this task reveals that observers look back and forth between the two figures, checking for distinct features (Just & Carpenter, 1976). This point was also made using simpler 2D figures where it was found that observers concentrate on significant milestone features when carrying out the task (Hochberg & Gellman, 1977), and that when such milestone features

are present, no “rotation” is found. In studies reported in (Pylyshyn, 1979b) I showed that the apparent “rate of rotation” depends both on the complexity of the figure and on the complexity of the post-rotation comparison task (I used a task in which observers had to indicate whether or not a misoriented test figure was embedded in the original figure). The dependence of the rotation speed on such organizational and task factors shows that whatever is going on in this case does not appear to consist in merely “rotating” one figure in a rigid manner into rough correspondence with the reference figure.

Second, even if the process of making the comparison in some sense involves the “rotation” of a represented shape, this tells us nothing about the form of the representation and does not support the view that the representation is pictorial. The notion that a representation maintains its shape because of the inherent rigidity of the image while it is rotated cannot be literally the case, notwithstanding the phenomenology. Since the *representation* is not literally being rotated – neither the brain cells that encode the figure nor any other form of encoding is being moved in a circular motion. At most what might be happening is that a representation of a figure is processed in such a way as to produce a representation of a figure at a slightly different orientation, and then this process is iterated (perhaps even continuously). There are probably good reasons, based on computational resource considerations, why the process might proceed by iterating over successive small angles (thus causing the comparison time to increase with the angular disparity between the figures) rather than attempt the comparison in one step. For example, small rotations result in small relative displacements of component parts of the form and decrease the likelihood of a new aspect coming into view. As a result incremental rotation might require less working memory to ensure the maintenance of the relative location among parts of the figure, using a constraint propagation method such as commonly used in computer vision systems. This was in fact the sort of reasoning that led Marr and Nishihara to hypothesize what they called a SPASAR mechanism for rotating simple vertices formed by pairs of lines and obtaining their projection onto a new reference frame (see Marr & Nishihara, 1976. A slightly different version that left out the details of the SPASAR mechanism, was later published in). This was an interesting idea that entailed a limited analogue operation on a small feature of a representation. Yet the Marr and Nishihara proposal did not postulate a pictorial representation, nor did it assume that a rigid configuration was maintained by an image in the course of its “rotation.” It hypothesized a particular operation on parts of a structured representation that was responsive to a computational complexity issue.

Like the paper folding task discussed earlier, the mental rotation phenomenon is robust and not cognitively penetrable, and so is not a candidate for a straightforward tacit knowledge explanation (as I tried to make clear in, Pylyshyn, 1979b). Rather, the most likely explanation is one that appeals to the computational requirements of the task and general architectural (i.e., working memory) constraints, and therefore applies regardless of the form of the representation. Nothing follows from the increase in time with angle concerning either the form of the representation of the figures or concerning how the representation as a whole must be manipulated. The problem of accounting for the linear relation of the angle between figures and the time to make the comparison is not resolved by talk or image “rotation.” Treating the phenomenology as explanatory does not help us to understand why or how the observed linear relationship occurs.

6.3.3 A Note concerning tacit knowledge and the criterion of *cognitive penetrability*

How can you tell whether certain observations made while a subject is solving a problem tell us about the nature of the architecture of the imagery system or about the person’s tacit knowledge and the way it is organized? One diagnostic I have advocated, discussed at length in (Pylyshyn, 1984a), is to test for the *cognitive penetrability* of the observations. Because a great deal of my criticisms of the conclusions that have been drawn from imagery research has been focused on this criterion, many of the counterarguments in the published literature have also concentrated on this criterion. And because so much of it has been based on misunderstandings of the role this criterion plays and how it is used, it is appropriate that I devote some space to a discussion of this issue.

The criterion is based on the assumption that if the reason for a particular pattern of observations (say of relative reaction times for different variants of the task) is that people are simulating a situation based on

their tacit knowledge, then if we alter the knowledge or the assumptions about the task, say by varying the instructions so as to change people's beliefs about the task situation, the observations may change accordingly, in a way that is rationally connected with the new beliefs. So, for example, if we instruct a person on the principles of color mixing we would expect the answer to the imaginal color mixing question discussed earlier to change appropriately. If you ask people to tell you when they see certain details on an image when they have been focusing on a certain place, the time it takes may or may not depend on how far away the detail is from the current focus, depending on whether subjects are led to believe that simulating the scanning time is relevant to the task (as we showed experimentally; see section 6.3.2.1). But as is the case with all methodological criteria, cognitive penetrability cannot be applied blindly. Even when some behavior depends on tacit knowledge, the behavior cannot always be appropriately altered with instructions, and you certainly can't discover what tacit knowledge subjects have or use by merely asking them why they did such and such or by asking them whether they know how the results should come out. This is a point that has been made forcibly in connection with tacit knowledge of grammar or of social conventions, which also typically cannot be articulated by members of a linguistic or social group, even though violations are easily detected.

It's important to note that just because an imagery-related phenomenon is cognitively impenetrable does not mean that the phenomenon provides evidence for the nature of the mental images or their mechanisms. Many behaviors are immune from cognitive influence: even beliefs may be resistant to change by merely being shown that they are false. As I noted earlier, there is no need to assume that *all* imagery phenomena are due to tacit knowledge and therefore that all patterns of observations in imagery experiments must be cognitively penetrable. An example in which the cognitive impenetrability of some part of a phenomenon has been taken as evidence against the tacit knowledge explanation of imagery, is an argument made by (Finke & Pinker, 1982) concerning a particular finding in a mental scanning experiment. As discussed earlier, in these experiments it is generally found that it takes more time to make judgments about things that are further away in the image. For example, (Finke & Pinker, 1982) found that the time required to judge that an arrow points to a dot increases the further away the dot is from the arrow. They argued that mental scanning could not have been due to tacit knowledge because even though subjects correctly predicted that judgments would take more time when the dots were further away, they failed to predict that the time would actually be longer for the shortest distance used in the study. Of course neither could the authors – and the reason is that the aberrant short-distance time was most likely due to some entirely different mechanism (perhaps attentional crowding) from that which caused the monotonic increase of time with distance, a mechanism not known to either the subjects or the experimenters! A major reason why one sometimes observes phenomena in imagery studies that subjects cannot predict rests on precisely a point recognized by (Finke & Freyd, 1989): most observed phenomena have more than one cause. Even when tacit knowledge is the main determiner of the phenomenon, other factors also contribute. Because of this cognitive impenetrability remains a *necessary but not sufficient* condition for a function to be due to the architecture of the cognitive system.

Another example of the mistaken inference from cognitive impenetrability to assumed properties of the imagery system concerns what has been called “representational momentum”. It was shown that when subjects observe a moving object and are asked to recall its final position from memory, they tend to misremember it as being displaced forward. (Freyd & Finke, 1984) attributed this effect to a property of the imagery system (i.e., to the nature of the imagery architecture). However, (Ranney, 1989) suggested that the phenomenon may actually be due to tacit knowledge. Yet it seems that at least some aspects of the phenomenon is not cognitively penetrable (Finke & Freyd, 1989). Does this mean that representational momentum must then be a property of the imagery architecture, as Freyd & Finke assumed? What needs to be recognized, in this and other such cases, is that there may be many other alternative explanations besides tacit knowledge or imagery architecture. In this particular case there is good reason to think that part of the phenomenon is actually visual. There is evidence that the perception of the location of moving objects precedes the actual location of such objects (Nijhawan, 1994). Also eye movement studies show that gaze precedes the current location of moving objects in an anticipatory fashion (Kowler, 1989, 1990). Thus even though the general phenomenon in question (the forms of visualized motion) may be attributable

to tacit knowledge, the fact that in these studies the moving stimuli are presented visually may result in the phenomena also being modulated by the visual system operating on the perceived scene. The general point in both these examples is that even genuine cases of failure of cognitive penetrability do not mean that the phenomena in question reveal properties of the imagery system.

A final point that needs emphasizing is that no criterion can be applied blindly to the interpretation of empirical results without making collateral assumptions. No cognitive mechanism can be observed directly; even something as clearly a part of the architecture as a “red” detector might or might not be used depending on the subject’s understanding and proclivities. A red detector can be used to find a car in a parking lot and the overall task of looking for the car is clearly cognitively penetrable. To distinguish the functioning of the detector from the functioning of the cognitive system in which it is embedded we need to set up the appropriate control conditions and we also need to make some (independently motivated) assumptions about how the task is carried out. As I have repeatedly said (e.g., Pylyshyn, 1978) observed behavior is a function of the *representation-process* pair, and one cannot be observed without the other. But that does not mean (as Anderson, 1978, has claimed) that we cannot in principle decide the nature of either (as I argued in my reply to Anderson, Pylyshyn, 1979c). The history of information-processing psychology has shown that the problems are not principled, but only practical. Cognitive penetrability is not a panacea, but a tool, much like RT and fMRI, to be used in carefully controlled experiments. While the general case can always be argued (since data always underdetermine theory) the cases of cognitive penetration that I cite here and elsewhere (Pylyshyn, 1981, 1984a) seem to me clear cases that show that particular hypotheses about the constraints imposed by the mental imagery mechanism are not tenable.

6.3.4 Summary of some possible reasons for observed patterns of imagery findings

As I mentioned throughout this section, there is more than one reason why particular systematic patterns of observations are found in studies of mental imagery, other than inherent properties of the imagery system (i.e., the architecture of mental imagery). Here is a summary of some of the reasons discussed in this section concerning why imagery experiments may produce the pattern of observations they do.

(1) First and foremost, the pattern may be due to the *use of tacit knowledge to simulate aspects of real-world events*, including the stages through which such events would tend to proceed and their relative durations. Subjects may cause the imagery results to come out in certain ways because they know how things in the world work and because they interpret the task as that of simulating how things would look if they were actually to happen in the world. We call the body of facts and beliefs that are brought to bear in this simulation, *tacit knowledge* because people may not be able to articulate what they know – as is generally the case with knowledge of naïve physics, of the conventions of social interactions, of the structure of one’s language, and perhaps even an implicit theory of what motivates other people (e.g., Nichols et al., 1996). Although such knowledge must be inferred indirectly by observing its consequence on behavior it must also meet the criteria of being knowledge – it must enter into inferential processes (so that its effect depends on what other things the observers know and what their utilities and goals are) and have generalized effects beyond a narrow domain.

(2) The pattern may be due not only to the content of tacit knowledge, but also to *how this knowledge is organized*. It is commonplace in psychology to find that in order to solve a problem people may be forced to go through a sequence of steps dictated by the way their knowledge is organized. A simple example of this is the task of saying what the *n*th letter is after a given letter in the alphabet. To do that most of us must go through the sequence of letters even though we clearly have tacit knowledge of all the letters and their order. That’s because knowledge of the alphabet happens to be organized in the form of a list to be accessed in sequence (presumably because it was learned that way). Similarly, the pattern we observe may arise from the fact that in using imagery certain access paths to relevant knowledge may be easier or more salient or more obvious. It is also commonplace in studies of reasoning that rewording a problem in a slightly different form results in it being either much easier or much more difficult to solve. Different ways of conceptualizing a task can similarly result in different patterns of problem solving (Hayes & Simon, 1976;

Kotovsky, Hayes & Simon, 1985). A prime candidate for this sort of explanation of an observed effect is the phenomenon concerning mental paper-folding, discussed in section 6.3.2.3.

(3) The pattern may be due to a *habitual way of solving certain kinds of problems* or to more frequent patterns of solution. This is the basis for the widely-studied phenomenon known in the problem-solving literature as “mechanization”, an example of which is the Luchins water jug experiment (Luchins, 1942). In this example subjects are shown a series of problems concerning measuring out a specified amount of liquid using containers of certain sizes. After successfully solving a series of problems using a certain combination of containers, subjects were unable to solve a new (equally simple) problem requiring a different combination of containers. Another is the so-called “functional fixedness” phenomenon studied by (Anderson & Johnson, 1966) in which people get stuck with one view of the function of an object (say viewing a matchbox as a container) and have a great difficulty solving a problem that is easily solved by viewing the same object in a different way (say as a potential shelf). This sort of effect is also common with tasks involving imagery, where we tend to use a particular, often habitual, way of imagining a situation.

(4) The pattern may be due to the nature of the task itself. As (Ullman, 1984) has argued, some tasks logically *require* a serial process for their solution. Depending on what basic operators we have at our disposal, it could turn out that the stages through which a solution process passes and the time it takes may be essentially determined by task requirements (see also Note 3 in Chapter 7). (Newell & Simon, 1972) have also argued that what happens in certain segments of problem solving (as it shows up, for example, in what they call a “problem behavior graph”) reveals little about subjects’ strategies because in those episodes subjects’ choices are dictated primarily by the demands of the task – i.e., subjects are doing what must be done to solve the problem or the obvious thing that any rational person would do in that state of the problem solving process.

(5) The pattern may also be due to general computational complexity constraints which result in trading off increased time for less complex operations, as hypothesized for mental rotation by the SPASAR theory (Marr & Nishihara, 1976), or as hypothesized by (Tsotsos, 1988) in connection with the question of why certain operations are carried out sequentially rather than in parallel. A candidate for this sort of explanation is the mental rotation phenomenon discussed in section 6.3.2.4.

(6) It is also possible that when we carry out experiments on mental imagery we will find effects that are not due solely to one of the above reasons, but to a combination of reasons. Phenomena may have multiple causes; it may be due to the interaction between the tacit knowledge used in the mental simulation and also certain properties of the cognitive architecture involved in reasoning. The architectural properties may be general ones (e.g., limitations of the short-term memory in which image-representations are stored during processing) or ones that are specific to creating and manipulating visual mental images.

6.4 Some alleged properties of images

6.4.1 Depiction and mandatory properties of representations

It has been frequently suggested that images differ from symbolic forms of representation (such as the “language of thought”) in that images stand in a special relationship to what they represent, a relationship often referred to as *depicting*. One way of putting this is to say that in order to depict some state of affairs the representation needs to correspond to the spatial arrangement it represents the way that a picture does. One of the few people who have tried to be explicit about what this means is Steven Kosslyn,⁵² so I quote from him at some length (Kosslyn, 1994, P5).

⁵² I don’t mean to pick on Steven Kosslyn who, along with Allan Paivio and Roger Shepard, has done a great deal to promote the scientific study of mental imagery. I focus on Kosslyn’s work here because he has provided what is currently the most developed theory of mental imagery and has been particularly explicit about his assumptions, and also because his work has been extremely influential in shaping psychologists’ views about the nature of mental imagery. In that respect his theory can be taken as the received view in much of the field.

“A depictive representation is a type of picture, which specifies the locations and values of configurations of points in a space. For example, a drawing of a ball on a box would be a depictive representation. The space in which the points appear need not be physical, such as on this page, but can be like an array in a computer, which specifies spatial relations purely functionally. That is, the physical locations in the computer of each point in an array are not themselves arranged in an array; it is only by virtue of how this information is “read” and processed that it comes to function as if it were arranged into an array (with some points being close, some far, some falling along a diagonal, and so on). In a depictive representation, each part of an object is represented by a pattern of points, and the spatial relation among these patterns in the functional space correspond to the spatial relations among the parts themselves. Depictive representations convey meaning via their resemblance to an object, with parts of the representation corresponding to parts of the object... When a depictive representation is used, not only is the shape of the represented parts immediately available to appropriate processes, but so is the shape of the empty space ... Moreover, one cannot represent a shape in a depictive representation without also specifying a size and orientation....”

This quotation introduces a number of issues that need to be examined closely. One idea we can put aside is the claim that depictive representations convey meaning through their resemblance to the objects they depict. This relies on the extremely problematic notion of resemblance, which has been known to be inadequate as a basis for meaning (certainly since Wittgenstein, 1953). Resemblance is neither necessary nor sufficient for something to have a particular meaning or reference: Images may resemble what they do not refer to (e.g. an image of John’s twin brother does not refer to John) and they may refer to what they do not resemble (an image of John taken through a distorting lens is an image of John even though it does not resemble him).

Despite its obvious problems, the notion of resemblance keeps surfacing in discussions of mental images, in a way that reveals how deeply the conscious experience of mental imagery contaminates conceivable theories of mental imagery. For example, (Finke, 1989) begins with the observation, “People often wonder why mental images resemble the things they depict.” But the statement that images resemble things they depict is just another way of saying that the conscious experience of mental imagery is in many ways similar to the conscious experience one would have if one were to see the thing one was imagining. Consider what it would be like if images did not “resemble the things they depict”? It would be absurd if in imagining a table one had an experience that was like that of seeing a dog? Presumably this is because (a) what it means to have a mental image of a chair is that you are having an experience like that of seeing a chair, and (b) what your image looks like, what conscious content it has, is something on which you are the final authority. You may be deceived about lots of things concerning your mental image. You may, and typically are, deceived about what sort of thing your image is (i.e. what form and substance underlies it), but surely you cannot be deceived about what your mental image looks like, or what it resembles. That is not an empirical fact about imagery, it’s just a claim about what the phrase “mental image” means.

What gives representations a role in thought is the fact that if it is possible for processes in the organism to obtain relevant information from them, and to make inferences from them, thereby making explicit some otherwise implicit information. There might be a weak sense of “resemblance” wherein a representation can be used to provide information about the appearance of an object or to allow such information to be made explicit when it was only implicit. But in this sense every representation of perceptible properties (including a description of how something looks) would be said to resembling its referent. Any stronger sense of resemblance inevitably imports an intelligent and knowledgeable agent for whom the representation “looks like” what it represents by eliminating the inherent many-to-many relation between an image and its meaning that Wittgenstein and others talked about. As Wittgenstein reminded us, an image of a man walking upstairs is the same as the image of a man walking downstairs backwards. An intelligent agent might take one of these interpretations over the other (especially if it was the agent’s own mental image) but would do so on the basis of reasoning from non-iconic considerations.

In contrast to the problematic criterion of resemblance, the proposal that images are decomposed into “parts” with the relations among parts of the image-representation in some way reflecting the part-structure and the spatial relationship among the corresponding parts of the world deserves closer scrutiny. It is closely related to a criterion discussed by (Sloman, 1971), although he suggested this as characteristic of analogue representations. Fodor and I referred to this sort of part-whole structure as the compositional character of representations and claimed that it is a requirement on any form of representation adequate to explain the representational capacity of intelligent organisms and to explain the capacity for thought and inference (Fodor & Pylyshyn, 1988). Thus if images are to serve as vehicles of thought they too must be compositional in this sense. And if they are compositional then they have what might be called interchangeable parts, much as lexical items in a calculus do. This however makes them more language-like (as in the “language of thought” proposal of Fodor, 1975) than pictorial and says little about the alleged depictive nature of images since it applies equally to any form of representation.

Another proposal in the quotation is that in depictive representations it is mandatory that certain aspects be made explicit. For example (according to Kosslyn) if you choose to represent a particular object you cannot fail to represent its shape, orientation and size. This claim too has some truth, although the question of which aspects are mandatory, why they are mandatory, and what this tells you about the form of the representation remains open. It is in fact a general property of representations that some aspects tend to be encoded (or assigned as default assumptions) if other aspects are. Sometimes that is true by definition of that form of representation or by virtue of the logical entailments of certain facts that are represented. So, for example, you can’t represent a token of a spoken or written sentence without making a commitment as to how many words it has, you can’t have a representation containing four distinct objects without implicitly representing the fact that there are four of them, and so on. Of course the converse is not true; the sentence “there are four plates on the table” does not contain four distinct representations of individual plates. Sometimes the tendency to represent certain clusters of properties may be just a matter of habit or of convention or of the frequent co-occurrence of the properties in the world: When you represent someone as riding a bicycle you may also represent them as moving the pedals (even though you needn’t have), when you represent someone as running you might also represent them as moving quickly, and so on, none of which is actually mandatory even if they are plausibly true. It may also be the case that certain patterns are frequent (if not mandatory) in visual images simply because they are frequent in the world being represented.

So the question is, when you represent some object in the form of an image is it mandatory that you represent its shape and size, and if so why? What about its color and shading? Must you represent the background against which you are viewing it, the direction of lighting and the shadows it casts? Must you represent it as viewed from a particular point of view? What about its stereoscopic properties; do you represent the changing parallax of its parts as you imagine moving in relation to it? Could you choose to represent any or none of these things? Is there something special about shape, orientation and size? It is clear that retinal size and location can be factored away from the representation of an object (in fact it is hard to demonstrate that these are even encoded into long term memory). But can shape and orientation also be factored away? Studies in rapid search suggest that we can identify the presence of a shape without identifying its location and we can identify both color and shape but miscombine them (Treisman & Schmidt, 1982). In fact, these studies appear to show that in representing shape, abstract properties such as having a “closed contour” may be factored apart from other properties of shape and miscombined. While these studies do not tell us which properties must be contained in an imaginal representation, they do suggest that in the process of visual encoding, shape, color, location and even closure can be factored apart from one another. In (Pylyshyn, 2001b) I suggested that very early in the visual process, all such properties (shape, color, location) are factored from (and are initially secondary to) the individuality of visual objects. What Kosslyn may have had in mind in the earlier quotation is that when you ask someone to imagine an object, say the letter “B,” the person will make a commitment to such things whether it is in upper or lower case. It seems as though you can’t imagine a “B” without imagining either the upper case letter “**B**” or a lower case letter “**b**”. But is this not another case of an implicit task requirement? Are you not being asked to describe what you see when you see a *printed token of a particular letter*? If you actually saw a printed

token of a letter you would have to see either a lower or an upper case letter, but not both and not neither. If someone claimed to have an image of a B that was noncommittal with respect to its case what would you say? You might be tempted to say that the person did not have a visual image at all, but only some vague sense of the letter. Yet most of our representations are like that. Clearly memory representations are noncommittal in various respects (see Chapter 1 for examples). In particular they can be noncommittal in ways that no picture can be noncommittal. Shall we then not call them images? Is an image generated in response to the letter-imaging example mentioned above not an image if it is non-committal with respect to its color or font or whether it is bold or italic? Such questions show the futility of assuming that mental images are like pictures. As the graphic artist M.C. Escher once put it (Escher, 1960, p7), "...a mental image is something completely different from a visual image, and however much one exerts oneself, one can never manage to capture the fullness of that perfection which hovers in the mind and which one thinks of, quite falsely, as something that is 'seen'."

One of the most important claims of the Kosslyn proposal, as expressed in the above quotation, is the idea that although images are inherently spatial, the space in question need not be physical but may be "functional". Both parts of this proposal (that images are spatial and that the relevant space might be a functional one) have been extremely influential and have led to entirely new lines of research, some of which has involved neural imaging. These lines of research, dealing with the claimed spatial nature of mental images, will be discussed separately in Chapter 7. For the present I will take up the question of whether there is any evidence to support the claim that images are the sorts of things that can be examined visually, as is clearly implied by the notion of "depiction" as a mode of representation.

6.5 Mental imagery and visual perception

It is fair to say that the most actively pursued question in contemporary imagery research has probably been the question of whether mental imagery uses the visual system. Intuitively the idea that imagery involves vision is extremely appealing for a number of reasons. One is that the experience of imagery is phenomenally very like the experience of seeing (indeed there have been (disputed) claims that when real perception is faint because of impoverished stimuli, vision and imagery can be indistinguishable, Perky, 1910a). I will return to the experiential similarity of vision and imagery later (section 6.5.5) and will raise the question of what significance ought to be attached to this experiential evidence. In this section I look at some of the psychophysical evidence for the involvement of vision in imagery. In Chapter 7 I will consider a new, and to many investigators a much more persuasive class of evidence for the involvement of vision in mental imagery, evidence that derives from neuroscience (especially neuroimaging studies).

In examining the question of whether (and in what way) vision may be involved in mental imagery, it is important to make a clear distinction between the visual system and the cognitive system, since cognition clearly is involved in some stage of what we call visual perception. In order to see how intimately imagery involves the visual system we must first provide some criteria for when we are observing the operation of the visual system, as opposed to the system that includes reasoning and cognition in general. This is why we need to have some characterization of the proprietary properties of the cognitively impenetrable aspects of vision. We need to identify a narrower technical sense of "visual system," as I attempted to do in (Pylyshyn, 1999) where I used the term "early vision" (possibly introduced by David Marr) to designate the proprietary modular part of vision that is unique to that modality. In investigating the involvement of the visual system in mental imagery we must also distinguish between effects attributable to the operation of a special visual architecture from effects attributable to the fact that in visual imagery we are concerned with different subject matter, for example we are typically concerned with visual (optical, geometrical) properties of some (actual or hypothetical) world. Our "null hypothesis" strategy (i.e., that in the absence of evidence to the contrary we shall assume that all thoughts take the same symbolic format) says that we need to ask whether a system that did not have a special *form* of encoding or a special architecture, might nonetheless exhibit the observed characteristics when it reasoned about visual properties, just as it might exhibit distinct characteristics when it reasoned about some other special subject matter, such as about emotions, feelings, interpersonal relations, or mathematics, or perhaps when it reasoned about such psychologically distinct

categories as animate versus inanimate things (e.g., there is reason to think that such subject matters may even involve different parts of the brain, Dehaene, 1995; Samson, Pillon & De Wilde, 1998). All of this means that we have to insist that certain distinctions be honored when asking whether imagery involves the visual system. In what follows I will examine a number of lines of evidence that have persuaded people that mental imagery involves the visual system, while keeping in mind the need for a finer technical distinction between “visual system” and the rest of the cognitive mind.

Many of the experiments described earlier (including the image scanning experiments and the studies involving projecting images onto visual stimuli) have been interpreted as suggesting that inspecting images involves the visual system. I have already discussed the finding that it takes longer to judge the presence of a small feature in a small image than in a large one. There is also a well-documented relation between the relative size of a pair of imagined objects and the time it takes to judge which one is larger. It is well-known that it takes longer to judge (by examining a visual image) whether a toaster is larger than a person’s head than to judge whether the toaster is larger than a horse. What is interesting about this phenomenon is not just the relation between time and imagined size, but the fact that this relation is the same as it is when real objects are being viewed, suggesting that the same visual mechanisms are being used. Although this phenomenon received a great deal of attention in early work on mental imagery it soon became clear that it had nothing to do with the putative *visual* aspect of mental images since the effect occurs with any comparison of magnitudes, including judgments of such abstract properties as the relative cost or attractiveness of different objects, or the relative magnitude of numbers (it is faster to judge that 374 is larger than 12 than that 23 is larger than 21). This more general phenomenon is called the “symbolic distance effect” (Friedman, 1978) and has been used to argue for some kind of an analogue form of representation, although the only thing that actually follows from the data is the plausibility that all magnitudes may be represented in some common manner (Gallistel, 1990).

There are many other phenomena involving the inspection of visual images that appear to parallel those that are found when real scenes are inspected, including the time it takes to judge the similarity of such imagined properties as color (Paivio & te Linde, 1980) or shape (Shepard & Chipman, 1970). Others are discussed in the following sections. This parallel between imagery and vision has led a number of people (e.g., Finke, 1980; Shepard, 1978b) to propose a theory of imagery which claims that in mental imagery, visual information in memory is fed into the visual system in place of information coming from the eyes. But it should be noted that even if the visual system is involved in mental imagery in this general way, it does not in any way speak in favor of the pictorial nature of mental images. As I noted in Chapter 1, the idea that vision involves the construction of an extended image of a scene has been thoroughly discredited. There is every reason to think that vision generates symbolic representations. So mental imagery may involve the very same kinds representations as does vision, and in neither case are these representations pictorial, notwithstanding our intuitive impression that there are pictures in our heads. Clearly the picture-theorists wish to make a stronger point. They wish to infer from the involvement of the visual system that images are something that are “seen” which, in turn, means that they must be pictorial in nature. The claim that the images function in this way is discussed in Chapter 7, in connection with the use of neuroscience evidence in pursuit of the picture-theory. In what follows I will describe some of the experimental evidence for the involvement of vision in mental imagery, without specifically raising the question of whether the evidence addresses the pictorial nature of images.

6.5.1 Interference between imaging and visual perception

One of the earliest objective sources of evidence that persuaded people that imagery involves the visual system is that the task of examining images can be disrupted by a subsidiary visual (or at least spatial) task. (Brooks, 1968) showed that reporting spatial properties from images is susceptible to interference when the response must be given by a spatial method (e.g. pointing) than a by verbal one (i.e., speaking). For example, if subjects are asked to describe the shape of the letter **F** by providing a list of right and left turns one would have to take in traveling around its periphery, their performance on this task is worse if the response is to point to the left or right (or to left- and right-pointing arrows) than if it is to say the words “left” and “right”. (Segal & Fusella, 1969, 1970) subsequently confirmed the greater interference between

perception and imagery in various same-modality tasks and also showed that both sensitivity and response bias (i.e., both measures d' and b , derived from Signal Detection Theory) were affected. Segal and Fusella concluded that “imagery functions as an internal signal which is confused with the external signal” (p 458). This conclusion, I believe, is the correct one to draw. But this does not imply that the same mechanism is involved in the two cases. What it implies, rather, is that the same type of representational contents are involved, or the same concepts are deployed. For the sake of argument, think of the representations in these studies as being in a common language of thought: What, in that case do the representations of visual patterns have in common with mental images? One obvious answer is that they are both about visual patterns. Like sentences about visual patterns, they all involve mentalese terms or concepts such as “bright,” “red,” “right angle,” “parallel to” and so on. It is not surprising that two responses requiring the same conceptual vocabulary would interfere. (That the linguistic output in the Brooks study is not as disruptive as pointing may simply show that spatial concepts are not relevant to *articulating* the words “left” or “right” once they have been selected for uttering, whereas these concepts *are* relevant to issuing the motor commands to move left or right.)

6.5.2 Visual illusions induced by superimposing mental images

Other studies suggesting that the visual system is involved in imagery are ones that show that projecting images of certain patterns onto displays creates some of the well-known illusions, such as the Müller-Lyer illusion, the Pogendorf illusion or the Herring illusion, or even the remarkable long-lasting orientation-contingent color aftereffect, called the McCollough effect.⁵³ As I have already suggested, studies that involve projecting images onto visual displays are special in that they provide an opportunity for the visual system to operate on the visual part of the input. In many cases the imagery-induced visual illusion results can be explained simply by assuming that in the visual case the effect was related to an attention-directing process induced by the secondary stimulus and therefore that the effect can be reproduced by attention manipulation alone. Take the following example of an imagery-induced Müller-Lyer effect. (Bernbaum & Chung, 1981) showed subjects displays such as those illustrated in Figure 6-8. Subjects were asked to imagine the endpoints of the lines connected to either the outside or the inside pairs of dots in this display (when the endpoints are connected to the inside pair of dots they produce outward-pointing arrows and when they are connected to the outside pair of dots they produce inward pointing arrows, as in the original Müller-Lyer illusion). Bernbaum & Chung (also Ohkuma, 1986) found that adding imagined arrowheads also produced the illusion, with the inward-pointing arrows leading to the perception of a shorter line than the out-ward pointing arrows. Such an effect is not only weak, but it is an ideal candidate for being a classical experimenter-demand effect of the sort discussed by (Predebon & Wenderoth, 1985). But for the sake of argument let us take these results as valid.

⁵³ Many of these studies have serious methodological problems that we will not discuss here in detail. For example, a number of investigators have raised questions about possible experimenter demand effects in many of these illusions (Predebon & Wenderoth, 1985; Reisberg & Morris, 1985). Few potential subjects have never seen illusions such as the Müller-Lyer (it is shown in virtually every introductory text in psychology, not to mention children’s books) so even if they do not acknowledge familiarity with the illusion, chances are good that they have some foreknowledge of it. Also the usual precautions against experimenter influence on this highly subjective measure were not taken (e.g., the experiments were not done using a double-blind procedure). The most remarkable of the illusions, the orientation-contingent color aftereffect, known as the McCollough effect, is perhaps less likely to lead to an experimenter-demand effect since not many people know of the phenomenon. Yet (Finke & Schmidt, 1977) reported that this effect is obtained when part of the input (a grid of lines) is merely imagined over the top of a visible colored background. But the Finke finding has been subject to a variety of interpretations as well as to criticisms on methodological grounds (Broerse & Crassini, 1981, 1984; Harris, 1982; Kunen & May, 1980, 1981; Zhou & May, 1993) so will not be reviewed here. Finke himself (Finke, 1989) appears to accept that the mechanism for the effect may be that of classical conditioning rather than a specifically visual mechanism.

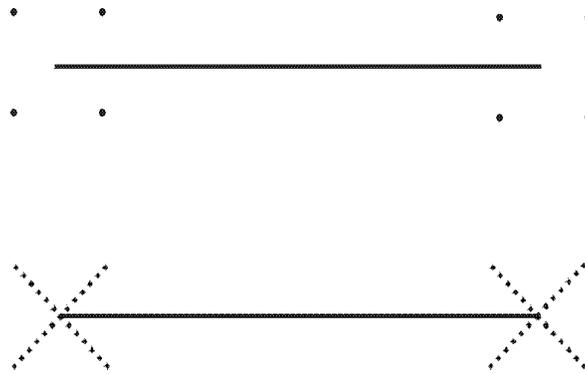


Figure 6-8 Figures used to induce the Müller-Lyer illusion from images. Imagine the end points being connected to the inner or the outer pairs of dots in the top figure (Bernbaum & Chung, 1981) or selectively look at the inward or outward arrows in the bottom figure (based on Goryo, Robinson & Wilson, 1984).

Consider first what may be involved in such illusions when the critical parts are actually viewed (as opposed to imagined), using the original Müller-Lyer illusion as our example. Explanations for this and similar illusions tend to fall into one of two categories. They either appeal to the detailed shapes of contours involved and to the assumption that these shapes lead to erroneous interpretations of the pattern in terms of 3D shapes, or they appeal to some general characteristics of the 2D envelope created by the display and the consequent distribution of attention or direction of gaze. Among the popular explanations of the Müller-Lyer illusion that fall into the first category is one due to Richard Gregory (Gregory, 1963), known as the “inappropriate constancy scaling” theory. This theory states that “Y” type (or inward-pointing) vertices, being generally associated with more distant concave corners of 3D rectilinear structures, are perceived as being further away, and therefore actually larger than they appear. This theory has been subject to a great deal of criticism and is unable to explain a number of findings, including why the illusion is obtained when inducing elements at the ends of the lines are not rectilinear vertices but various sorts of fork-like curves that do not lend themselves to a 3D interpretation (see the review in Nijhawan, 1991). Theories in the second category include ones that attribute the illusion to attention and to mechanisms involved in preparing eye-movement. For example, one theory (Virsu, 1971) claims that the illusion depends on the distance between the vertex and the center of gravity of the arrowhead, and appeals to the tendency to move one’s eyes to the center of gravity of a figure. The involvement of eye movements in the Müller-Lyer illusion has also been confirmed by (Bolles, 1969; Coren, 1986; Festinger, White & Allyn, 1968; Hoenig, 1972; Virsu, 1971). Another example of the envelope type of theory is the framing theory (Brigell, Uhlarik & Goldhorn, 1977; Davies & Spencer, 1977) which uses the ratio of overall figure length to shaft length as predictor. Such envelope-based theories have generally fared better than shape-based theories not only on the Müller-Lyer illusion, but in most cases in which there are context effects on judgments of linear extent. What is important about this from our perspective is that these explanations do not actually appeal to pattern-perception mechanisms and therefore are compatible with attention-based explanations of the illusions. The “envelopes” of the figures in many of these cases can be altered by assigning attention (or visual indexes) to objects or places or regions in the display.

Further evidence that attention can play a central role in these illusions comes from studies that actually manipulate attention focus. For example, it has been shown (Goryo et al., 1984) that if both sets of inducing elements (the outward and inward arrowheads) were present, observers could selectively attend to one or the other and obtain the illusion appropriate to the one to which they attended. This is very similar to the effect demonstrated by (Bernbaum & Chung, 1981) but without requiring that any image be superimposed on the line. (Coren & Porac, 1983) also confirmed that attention alone could create, eliminate or even reverse the Müller-Lyer illusion. In addition, the relevance of imagery-induction of the Müller-Lyer illusion to the claim that imagery involves the visual system is further cast into doubt when one

recognizes that this illusion, like many other imagery-based phenomena, also appears in congenitally blind people (Patterson & Deffenbacher, 1972).

There have been a number of other claims of visual illusions caused (or modified) by mental imagery (e.g., Wallace, 1984a, 1984b). When such image-induced effects on illusions are not due to experimental-demand effects (as they may well be in some cases, where results cannot be replicated under controlled conditions Predebon & Wenderoth, 1985; Reisberg & Morris, 1985) they are all subject to the interpretation that the effect is mediated by the allocation of focal attention. Indeed the attention-mediation of such effects was shown explicitly in the case of ambiguous motion-illusion by (Watanabe & Shimojo, 1998).

6.5.3 Imagined versus perceived motion

Another way to examine the possible involvement of the visual system in imagery is to select some phenomenon known to occur in the early stages of vision and to ask whether it occurs in mental imagery. A good candidate is one that involves adaptation to motion, which is known to have a locus in early vision (in fact in visual cortex). When a region of the visual field receives extensive motion stimulation, an object presented in that region is seen to move in the opposite direction to the inducing movement (the “waterfall illusion”) and a moving object is seen as moving more slowly (presumably because the motion detection cells in visual cortex have become fatigued). This phenomenon is of special interest to us since the adaptation is known to be retinotopic, and therefore occurs in a retinotopically mapped part of the visual system. Convinced that the visual system is involved in mental imagery, (Gilden, Blake & Hurst, 1995) set out to show that the motion of an imagined object is similarly affected by the aftereffect of a moving field. They had subjects gaze for 150 seconds at a square window on a screen containing a uniformly moving random texture. Then they showed subjects a point moving towards that window and disappearing behind what appeared to be an opaque surface, and they asked subjects to imagine the point continuing to move across the previously stimulated region and to report when the point would emerge at the other side of the surface. Gilden et al. did find an effect of motion adaptation on imagined motion, but it was not exactly the effect they had expected. They found that, as expected, when the point was imagined as moving in the same direction as that of the inducing motion field (i.e., against the motion aftereffect) it appeared to slow down (it took longer to reach the other side of the region). However, when the point was imagined as moving in the opposite direction to the inducing motion field (i.e., in the same direction as the motion aftereffect), the point appeared to speed up (it reached the other side in a shorter time). The latter effect is *not* what happens with real moving points. In visual motion adaptation, motion appears to slow down no matter which direction the inducing motion field moves, presumably because all motion sensitive receptors had been satiated or fatigued. But, as Gilden et al. recognized, the effect they observed is exactly what one would expect if, rather than imagine the point moving uniformly across the screen, subjects imagined the point as being located at a series of static locations along the imagined path. This suggests a quite different mechanism underlying imagined motion. We know that people are very good at computing time-to-contact (or arrival time) of a uniformly moving object at a specified location. This is why we are so good at estimating when a baseball will arrive at various critical places (e.g., over the batter’s box, at a particular place in the field). What may be going on in imagined motion is that people may simply pick out one or more marked places (e.g., elements of texture) along the path, using the visual indexing mechanism discussed earlier, and then compute the time-to-contact for each of these places.

We explicitly tested this idea (Pylyshyn & Cohen, 1999) by asking subjects to extrapolate the motion of a small square that disappeared behind an apparent opaque surface. They were asked to imagine the smooth motion of the square in a dark room. At some unpredictable time in the course of this motion the square would actually appear, as though coming out through a crack in the opaque surface, and then receding back through another crack, and subjects would indicate whether it had appeared earlier or later than when their imagined square reached that crack. This task was carried out in several different conditions. In one condition the location of the “cracks” where the square would appear and disappear was unknown (i.e., the cracks were invisible). In another condition the location at which the square was to appear was known in advance: it was indicated by a small rectangular figure that served as a “window” through which, at the appropriate time, subjects would briefly view the square that was moving behind the

surface (the way the squares appeared and disappeared in the window condition was identical to that in the no-window condition except that the outline of the window was not visible in the latter case). And finally in one set of conditions the imagined square moved through total darkness whereas in the other set of conditions the path was marked by a sparse set of dots that could be used as reference points to compute time-to-contact. As expected, the ability to estimate where the imagined square was a various times (measured in terms of decision time) was significantly improved when the location was specified in advance and also when there were visible markers along the path of imagined motion. Both of these findings confirm the suggestion that what subjects are doing when they report “imagining the smooth motion of a square” is selecting places at which to compute time-to-contact (a task at which people are very good; DeLucia & Liddell, 1998) and are merely thinking that the imaginary moving square is at those places at the estimated times. According to this view, subjects are thinking the thought “now it is *here*” repeatedly for different visible objects (picked out by the visual indexing mechanism mentioned earlier), and synchronized to the independently computed arrival times. This way of describing what is happening requires neither the assumption that the visual system is involved (other than the attentional indexing mechanism) nor does it need to assume that an imagined square is actually moving through some mental space and occupying each successive position along a real spatial path. Indeed there is no need to posit any sort of space except the visible one that serves as input to the time-to-contact computation.

6.5.4 Extracting novel information from images: Visual (re)perception or inference?

It is widely held that one of the purposes of mental images is that they can be examined visually in order to discover new visually properties or see new visual interpretations or reconstructions. It would therefore seem important to ask whether there is any evidence for such visual reconstructions. This empirical question turns out to be more difficult than one might have expected to answer univocally, for it is clear that one can draw *some* conclusions by examining images that were not explicitly present in, say, the verbal description under which it was imagined. So if I ask you to imagine a square and then to imagine drawing in both diagonals, it does not seem surprising that you can tell that the diagonals cross or that they form an “X” shape. This does not seem *prima facie* to qualify as an example showing that images are interpreted *visually*. On the other hand, suppose I ask you to imagine two parallelograms, one directly above the other, and then connect each vertex of the top figure to the corresponding vertex of the bottom one. What do you see? As you keep watching, what happens in your image? When presented visually, this figure consistently leads to certain phenomena that do not appear in mental imagery. The signature properties of spontaneous perception of certain line drawings as depicting three-dimensional objects and spontaneous reversals of ambiguous figures do not appear in this mental image (which happens to be that of a Necker Cube, described accurately, if somewhat unconventionally).

But what counts, in general, as a visual interpretation as opposed to an inference? I doubt that this question can be answered without a sharper sense of what is meant by the term “visual”, a problem to which I have already alluded. Since the everyday (pretheoretical) sense of the notion of “vision” clearly involves most of cognition, neither the question of the involvement of vision in imagery nor the question about visual reconstructions can be pursued nontrivially in terms of this broad notion of vision. At the very least we need a restricted sense of what is to count as vision or as a visual interpretation. I have elsewhere argued that there is good evidence for an independent visual module, which I called “early vision” (Pylyshyn, 1999). Because early vision is the part of the visual system that is unique to vision and does not involve other more general cognitive processes (such as accessing long-term memory and inference), it would be appropriate to refer questions about reinterpretation of images to phenomena characteristic of this system. Clearly, deciding whether two intersecting lines form an “X” is not one of these phenomena, nor is judging that when a D is placed on top of a J the result looks like an umbrella: You don’t need to use the early visual system in deciding that. All you need is an elementary inference based on the meaning of such phrases as “looks like an umbrella” (e.g., has a upwardly convex curved top attached below to a central vertical stroke – with or without a handle at the bottom)! Thus these the sorts of examples (which were used in Finke, Pinker & Farah, 1989), cannot decide the question of whether images are depictive or pictorial or, more importantly for present purposes, whether they are *visually* (re)interpreted. Presenting

information verbally and asking people to imagine the pattern being described is one way to get at the question of whether the interpretation can be classed as visual (as in the Necker cube example I cited above).

Another way is to present a normally ambiguous pattern and then take it away and ask whether other new visual interpretations occur when the display is no longer there. This case, however, presents some special methodological problems. Not all ambiguities contained in pictures are visual ambiguities and similarly not all reinterpretations are visual reconstructions. For example, the sorts of visual puns embodied in some cartoons (most characteristically in so-called “doodles,” illustrated in Chapter 1 (see also URL: <http://www.weonly.com/doodles> for examples) do rely on ambiguities, but clearly not on ones that reply on different visual organizations being produced by the early visual processes. By contrast, the reversal of figures such as the classical Necker Cube is at least in part the result of a reorganization that takes place in early vision. Do such reorganizations occur with visual images? In order to answer that questions we would have to control for certain alternative explanations of apparently visual reinterpretations. For example, if a mental image appeared to reverse, it might be because the observer knew of the two possible interpretations and simply replaced one of its interpretations with the other. This is the alternative view that many writers have preferred in the past (Casey, 1976; Fodor, 1981). Another possibility might be that the observer actually computed both alternatives, but only reported one. This sort of simultaneous computing of two readings for a brief time has been frequently reported in the case of sentence ambiguities (e.g., Swinney, 1979), where it was shown that in cases of lexical ambiguity, both interpretations are briefly available (and both were shown to prime associated words) even though the person was only aware of one and only one was recalled. Similarly, in (Pylyshyn, 1999), I argued that notwithstanding the encapsulated nature of early vision, one of the ways that the cognitive system might still be able to effect the visual interpretation of ambiguous figures is if both possible interpretations were initially available so that the cognitive system could select among them based on their plausibility. Notwithstanding the methodological difficulties in obtaining a clear answer to the question of whether mental images allow visual reconstructions, a number of studies have been carried out on this question.

(Chambers & Reisberg, 1985) was the first to put the question of possible ambiguous mental images to an empirical test. They reported that no reversals or reinterpretations of any kind took place with mental images. Since that study was reported there have been a series of studies and arguments concerning whether images could be visually (re)interpreted. (Reisberg & Chambers, 1991; Reisberg & Morris, 1985) used a variety of standard reversal figures and confirmed the Chambers and Reisberg finding that mental images of these figures could not reverse. (Finke et al., 1989) have taken issue with these findings, citing their own experiments involving operations over images (which were mentioned briefly in section 6.1), but as I suggested above it is dubious that the reinterpretation of the superposition of their simple familiar figures should be counted as a *visual* reinterpretation. Moreover, even if the interpretations studied by Finke et al. were considered visual interpretations, there remains the serious problem of explaining why clear cases of visual interpretations, such as those studied by Chambers and Reisberg, do not occur with images.

A more direct and detailed exploration of the question of whether mental images can be ambiguous was undertaken by (Peterson, 1993; Peterson, Kihlstrom, Rose, & Glisky, 1992) who argued that certain kinds of reconstructions of mental images does take place. Peterson first distinguished different types of image reinterpretations. In particular she distinguished what she calls *reference-frame realignments* (in which one or more global directions are reassigned in the image, as in the Necker cube or rabbit-duck ambiguous figures) from what she calls *reconstructions* (in which reinterpreting the figure involves assigning new meaning to its parts, as in the wife/mother-in-law or snail/elephant reversing figures). I will refer to the latter as *part-based reconstructions* to differentiate them from other kinds of reconstructions (since their defining characteristic is that their parts take on a different meaning). A third type, figure-ground reversal (as in the Rubin vases), was acknowledged to occur rarely if ever with mental images (a finding that was also systematically confirmed by Slezak, 1995, using quite different displays). Among her findings, Peterson showed that reference-frame realignments do not occur in mental images unless they are cued by either explicit hints or implicit demonstration figures, whereas some part-based reconstructions occurred with 30% to 65% of the subjects.

Recall that our primary concern is not with whether any reinterpretations occur with mental images. The possibility of some reinterpretation depends upon what information or content-cues are contained in the image, which is orthogonal to question of the mechanisms used in processing it. What I am concerned about is whether the format of images is such that their interpretation and/or reinterpretation involves the specifically visual (i.e. the early vision) system as opposed to the general inference system. The crucial question, therefore, is how Peterson's findings on reinterpreting mental images compares with the reinterpretations observed with ambiguous visual stimuli. The answer appears to be that even when reinterpretations occur with mental images, they are qualitatively different from those that occur with visual stimuli. For example, (Peterson, 1993) showed that whereas reference-frame reversals are dominant in vision they are rare in mental imagery while the converse is true for part-based reconstruals. Also the particular reconstruals observed with images tend to be different from those observed with the corresponding visual stimuli. Visual reconstruals tend to fall into major binary categories – in the case of the figures used by Peterson et al. these are the duck or rabbit, or the snail or elephant categories, whereas in the imagery case subjects provided a large number of other interpretations (which, at least to this observer, did not seem to be clear cases of distinctly different appearances – certainly not as clear as the cases of the Necker Cube reversal or even the reconstruals observable when the shapes in Figure 6-9 are rotated). The number of subjects showing part-based reconstruals with mental images dropped by half when only the particular interpretations observed in the visual case were counted. Reinterpretation of mental images is also highly sensitive to hints and strategies, whereas there is reason to doubt that the early stages of vision are sensitive to such cognitive influences (Pylyshyn, 1999), although clearly later stages are. The reason for these differences between imagery and vision is not clear, but they add credence to the suggestion that what is going on in the mental image reconstruals is not a perceptual (re)interpretation of a generated picture, but something else, perhaps the sort of inference and memory-lookup based on shape properties that goes on in the decision stage of vision, after early vision has generated shape-descriptions. This is the stage at which beliefs about the perceived world are established so we expect it to depend on inferences from prior knowledge and expectations, like all other cases of belief fixation. It seems quite likely that parts of the highly ambiguous (though not clearly bistable) figures used by Peterson et al. might serve as cues for inferring or guessing at the identity of the whole figure (for illustrations of these figures, see Peterson, 1993). Alternatively, as suggested earlier, several possible forms might be computed by early vision (while the figures were viewed) and stored, and then during the image-recall phase a selection might be made from among them based on a search for a meaningful familiar shape in long-term memory. While in some sense all of these are reinterpretations of the mental images, they do not all qualify as the sort of visual "reconstruals" of images that show that mental images are pictorial entities whose distinct perceptual organization (and reorganization) is determined by the early vision system. Indeed they seem more like the kind of interpretations one gets from Rorschach inkblots.

The clearest sources of evidence I am aware of that bears on that question is provided by studies carried out by Peter Slezak (Slezak, 1991, 1992, 1995). Slezak asked subjects to memorize pictures such as those in Figure 6-9. Then he asked them to rotate the images clockwise by 90 degrees and to report what they looked like. None of his subjects was able to report the appearance that they could easily report by rotating the actual pictures. The problem was not with their recall or even their ability to rotate the simple images, it was with their ability to recognize the rotated image in their mind's eye. What is special about these examples is that the resultant appearance is so obvious – it comes as an "aha!" experience when carried out by real rotation. Unlike the figures used by (Finke et al., 1989), these shapes were not familiar, nor do they contain unique "landmark" features (which can influence the ability to recognize a rotated pattern – see Hochberg & Gellman, 1977) and their appearance after the rotation could not easily be inferred from their representation. Moreover, it appears that subjects had all the relevant information since when they drew the figures from memory and then rotated them they *did* see the other construals.



Figure 6-9. Orientation-dependent figures used by (Slezak, 1991). To try these out, memorize the shape of one or more of the figures, then close your eyes and imagine them rotated clockwise by 90 degrees (or even do it while viewing the figures). What do you see? Now try it by actually rotating the page. (from Slezak, 1995)

6.5.5 What about the experience of “visualizing”?

It may well be that the most persuasive reason for believing that mental imagery involves the visual perception is the subjective one: Mental imagery is accompanied by an experience very similar to that of seeing. As I remarked at the beginning of this article, this sort of phenomenal experience is very difficult to ignore. Yet studies of visual perception demonstrate that introspection is highly suspect because it trades on the failure to distinguish between the content of our experience (what we are imagining) and the causal entities in our head that are responsible for the way things unfold in our mind. There is the very strong temptation to reify the image content – to make what Titchener called the “stimulus error” of attributing to a mental state the properties of a world that could give rise to the mental state. As I remarked earlier, the experience of imaging is not an experience that reveals the form of the image; rather it reveals the content the image. The experience of the image tells us what it is an image of. Because of this it is totally plausible that both vision and imagery lead to the same kind of experience because in both cases the experience might be mediated by the same kind of internal state. In fact, a common view, made explicit in (Shepard, 1978b), is that imagery is nothing but the substitution of the mental states normally associated with visual perception, though without an external visual stimulus. Shepard notes that because the image is not external we cannot actually describe it. But if we *could* externalize it, by mapping from a brain state back to a stimulus that would have been its distal cause, it would look like a scene – as illustrated by Shepard in Figure 6-10 and Figure 6-11.

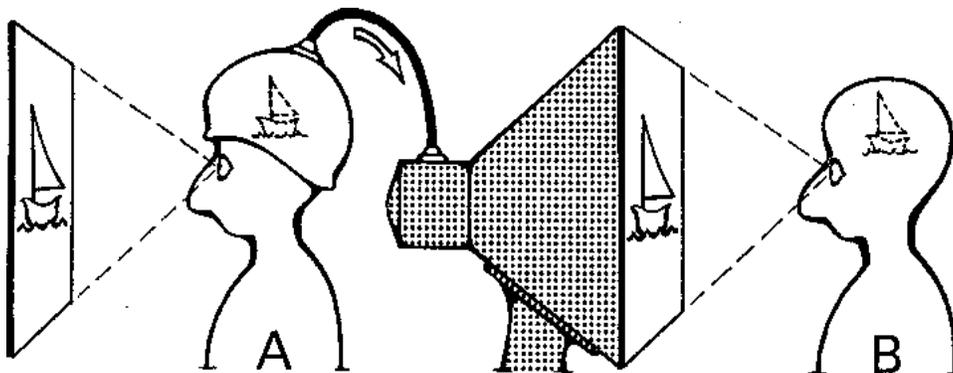


Figure 6-10. Illustration of a hypothetical mechanism that externalize the brain states involved in visual perception so another person might see it (from Shepard, 1978b).

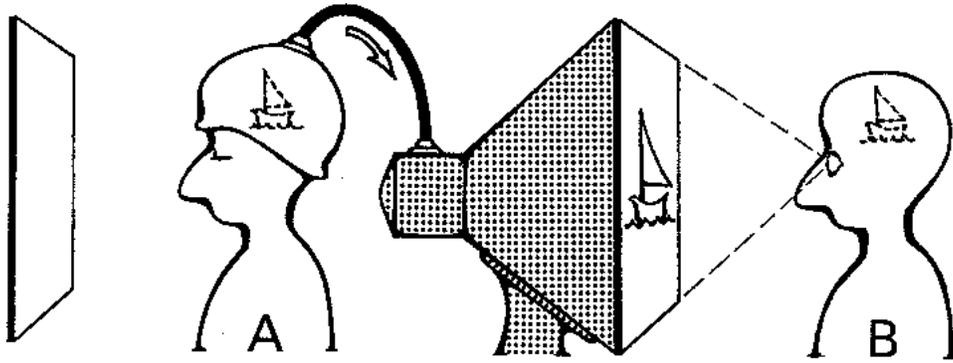


Figure 6-11. Illustration of the parallel externalization of a mental image (from Shepard, 1978b).

This, as Shepard recognized, does not support the view that images are pictorial in any sense, although it does assume that whatever mental images are, they involve the same (or similar) brain states as are involved in vision. The claim that the experience of mental images arises from the same brain states as occur in visual perception does not entail that the internal state is underwritten by a pictorial, as opposed to a symbolic structure in the brain. In addition, introspection also does not tell us what stage in the process of vision or imagery is associated with our conscious experience. The experience might correspond to a high level of the analysis of the visual information, say at the point where the stimulus is recognized as something familiar (e.g., Crick & Koch, 1995; Stoerig, 1996, suggest that the locus of our awareness occurs higher than primary visual cortex). In fact there is good reason to think that this is the correct view given that a picture is infinitely ambiguous (as we saw in Chapter 1). Yet presumably a mental image is not ambiguous to the person whose image it is. Thus the experience of imaging would not actually be the experience of *seeing* (in the sense of early vision), but rather of recognizing or of *seeing as*, to use a helpful philosophical distinction. In that case what we experience does not consist of pictorial entities; indeed the sorts of considerations discussed in Chapter 1 strongly suggest that visual perception itself eventuates in conceptualized, symbolically-encoded mental representations.

In addition to these problems about conscious contents, it is also likely that the distinction between information processing episodes of which we are conscious and those of which we have no awareness marks a scientific natural kind; the kind of demarcation that can help to focus our attention on the relevant causal variables. It could turn out that imagery *is*, after all, a special form of information processing, but that it only overlaps partially with episodes involving visual awareness. It *could* turn out that the correct analysis of the type of information processing involved in mental imagery does not distinguish between episodes of which we have a sensory-like awareness and those of which we do not. In other words, it could turn out that there is a theoretically interesting and distinct form of information processing which is sometimes accompanied by the phenomenology we associate with imagery and sometimes not. Already there has been talk of “unconscious imagery” and there is evidence that most experimental results obtained in studying imagery (such as the mental scanning phenomena, the size or zoom phenomena) can be obtained from congenitally blind subjects (see, for example, Barolo, Masini & Antonietti, 1990; Cornoldi, Bertuccelli, Rocchi, & Sbrana, 1993; Cornoldi, Calore & Pra-Baldi, 1979; Craig, 1973; Dauterman, 1973; Dodds, 1983; Easton & Bentzen, 1987; Hampson & Duffy, 1984; Hans, 1974; Heller & Kennedy, 1990; Johnson, 1980; Jonides, Kahn & Rozin, 1975; Kerr, 1983; Marmor & Zaback, 1976; Zimler & Keenan, 1983) or from subjects who profess little if any experience of mental imagery (see Chapter 7 for more on the dissociation between imagery and vision). Also the status of reports of vividness of images is controversial. Subjective vividness does not appear to correlate with performance in a great many imagery tasks. For example, it has been reported that the ability to recall visual experiences is either uncorrelated (Berger & Gaunitz, 1977) or even negatively correlated with vividness of the experience (Chara & Hamm, 1989), although the confidence level of the reports is correlated with vividness (McKelvie, 1994) as is performance tasks such as inducing visual illusions by superimposing imaginal patterns over perceived ones (see section 6.5.2). But

other tasks show differences between vivid and nonvivid imagers that are hard to interpret in terms of their use of mental images (see, e.g., Wallace, 1991).

In assessing the evidence from phenomenology one needs to seek corroborating objective evidence for informational differences between mental episodes accompanied by the experience of seeing and mental episodes that are accompanied by some other experience. A great many studies suggest that unconscious states play the same role in cognition as do conscious states (e.g., stimuli of which we have no conscious awareness appear to influence perception and attention the same way as stimuli of which we are aware, Merikle, Smilek & Eastwood, 2001). But there is also some different information processing and neurophysiological correlates of episodes accompanied by awareness (Dehaene & Naccache, 2001; Driver & Vuilleumier, 2001; Kanwisher, 2001). What I have argued, here and elsewhere, is just that we are not entitled to take the content of our experience as reflecting, in any direct way, the nature of the information processing activity (as one does in what Pessoa, Thompson & Noë, 1998, call the “analytical isomorphism” assumption). In particular, the evidence does not entitle us to conclude that episodes of reasoning accompanied by the experience of seeing involve accessing uninterpreted, spatially-displayed depictive representations (i.e., pictures) using the early visual system.

Finally, cognitive science has no idea what to make of the subjective impression that we are “seeing” or “hearing” some particular appearance since this is tied up with the deeply mysterious questions of consciousness. It is tempting to view our experience itself as playing a causal role – as having causal powers. We say such things as that we scan our image or zoom in to see a small detail in it or that we remember a certain emotional crisis by thinking of it in a certain way (e.g., as having a spiral shape). I am sure that there is *some* sense in which these are true reports. But this way of putting it suggests that how a cognitive episode is experienced *caused* a certain observable consequence, rather than the cause being some underlying physical state. Taken literally, such claims entail a dualist (or at least an interactionist) metaphysics. They claim that there can be causes that are not physical (i.e., that do not follow natural physical law). While that is a coherent position one could take, it is not one that most writers on mental imagery would want to defend. What we would prefer to defend is the notion that underlying a certain type of experience are certain physical/biological properties and it is these properties that are the causes of the behavior. A particular experience, say the experience of “seeing in the mind’s eye”, is not a possible natural property, so the statements that contain references to such experiences are not literally what their authors want to claim. But if it’s not literally the case that I behave in certain ways because of how I experience some mental episode, then I need a different way to describe the causal sequence, a way that will perforce not describe the causal events as I do in everyday discourse; a way that does not mention that I seem to be seeing a picture in my mind’s eye.

7. SEEING WITH THE *MIND'S EYE* 2: SEARCHING FOR A SPATIAL DISPLAY IN THE BRAIN

One of the most widely accepted claims about mental images is that they are “spatial”; and among the most frequently cited demonstrations of this claim are the mental scanning experiments discussed in section 6.3.2.1. There I argued that it is unwarranted to conclude that because it takes longer to scan attention across greater imagined distances that images must “preserve” metric spatial information (Kosslyn et al., 1978) – at least not if by “preserving” distances one means that images *have* spatial properties such as size and distance, rather than simply encoding such properties (in *any* way). Yet the alleged spatiality of mental images is central to the claim that images are *depictive* and thus unlike any possible “language of thought.”

The claim that images have spatial properties comports with one’s intuitions about mental images, but it raises some interesting and subtle questions about what it means to *have* spatial properties, and whether there could be any sense to this notion apart from the literal claim that images are written on some physical surface, presumable on some surface in the brain. In what follows I will examine the claim that images are spatial and then examine the recent evidence that has been presented and interpreted as bearing on this question.

7.1 Real and “functional” space

As mentioned in the previous chapter, one of the more interesting claims about images made by Kosslyn (e.g., in the quotation cited in Chapter 6, section 6.4) and many other writers (e.g., Denis & Kosslyn, 1999), is that images are laid out spatially in a *functional*, rather than in a physical space – where the notion of a “functional” space is introduced by example, as something like a matrix or array data structure in a computer. This is a seductive idea because it appears to allow us to claim that images are spatial without also committing us to claiming that they are actually laid out in real space in the brain or in some other physical medium. It also appears to give some meaning to the claim that images somehow incorporate (or “preserve”) distances as well as sizes. Because the idea that images are somehow spatial has been so influential in theorizing about mental imagery, I will devote this chapter to a discussion of this claim and to some of the recent evidence cited in support of it. Before going into the evidence, however, I consider what it might mean to claim that images are spatial. Then I will argue that the appeal to a functional space is actually empty and merely restates the phenomenon we are trying to explain.

The problem with the “functional space” proposal is that functional spaces do not intrinsically have any particular properties. Being “functional” they are not subject to any natural laws and therefore can be assumed to have whatever properties are needed in order to account for the experimental data. Because they have no inherent properties other than those that are extrinsically assumed, they can explain any findings whatever. Or, to put it more positively, if the extrinsic assumptions provide any explanatory advantage at all, they can equally well be adjoined to a theory that assumes *any* form of representation, not just a pictorial one. They can, for example, be added to a theory that says that the form of information underlying images is a “language of thought.” Despite this clear inadequacy of the functional space proposal, the idea remains widely accepted in psychology. The reason for this seductive quality of the proposal is itself quite revealing and so I will devote part of this chapter to discussing how the functional space idea connects with the literal space (the display-in-the-head) hypothesis, and how it maintains a very strong pull on contemporary research on mental imagery which itself has led to certain lines of investigation of mental imagery, particularly in neuroscience.

In the computational model of mental imagery described in (Kosslyn, Pinker, Smith, & Shwartz, 1979), the inner “screen” on which images are “displayed” is a matrix of elements – a computer data structure that corresponds to a two-dimensional matrix. It functions like a two-dimensional display in several respects. Graphical elements, such as points, lines, contours, regions, and other components of figures are written on the matrix by filling designated cells which correspond to places on the image, defined in terms of quantized

Cartesian coordinates (the pairs of matrix indexes). The principles for generating figures are explicitly stated, as are principles for reading off figural properties (at least in principle, if not in any actual worked-out system). For example, in order to examine a certain part of a figure after examining another part, the system has to move a locus of processing (corresponding to its focal attention) through intermediate points along the path from one figure part to the other. This is done by incrementing the (x or y) indexes by one. The matrix itself appears to *intrinsically* contain unfilled places that serve as potential locations of figural elements, so that empty places appear to be explicitly represented. As Kosslyn claimed in the earlier quotation, in this kind of representation, "...each part of an object is represented by a pattern of points, and the spatial relation among these patterns in the functional space correspond to the spatial relations among the parts themselves. ... not only is the shape of the represented parts immediately available to appropriate processes, but so is the shape of the empty space..." In other words, empty places are explicitly displayed, along with filled places, so that regions between contours are formed and displayed as a natural consequence of displaying contours. This form of representation appears to embody the criteria for being a depictive representation as described in the quotation. In this way the model appears to (at least in principle) account in a natural way for much of the relevant data, so what else could we ask for?

As we saw when we discussed the mental scanning results (and the mental color-mixing example), in order to provide an explanation it is not enough that a model exhibit certain patterns of observed behaviors. We still need to say *why* these behaviors arise. As with all the examples I discussed in Chapter 6 (including the mystery code-box example), it makes a great deal of difference whether a particular generalization holds because (a) the system uses its beliefs about the world along with its reasoning capacity to simulate some behavior it believes would occur in the imagined situation, or because (b) the principle is inherent in the mechanism or medium or architecture of the system that displays and examines images. So we need to ask which of these is being claimed in the case of the matrix (or any other "functional space") model of the image? The answer is crucial to whether the model provides an explanation of the experimental findings or merely summarizes them, the way a table or other descriptive data summary might do.

Here the image theorist is caught on the horns of a dilemma. On the one hand the system (say the one that uses a matrix data structure) might be viewed as a model of the architecture (or, equivalently, the format or the medium) involved in mental imagery. If that is the case its properties ought to remain fixed and they ought to explain the principles by which the imagery system works (and perhaps even provide some suggestions for how it might be implemented in the brain). This alternative (which we might call a "model of the architecture of mental imagery") can be subjected to empirical scrutiny, using, among other techniques, the criterion of cognitive penetrability. The architectural version of the functional space proposal entails that the observed properties will not change with changes in the person's beliefs about the task. On the other hand, the matrix model might be thought of as simply summarizing the pattern of people's behavior in particular circumstances (e.g., the increase in time to switch attention to more distant places in the image, or the increase in time to report details from a "smaller" image), with no commitment as to *why* this pattern of behavior arises. In this purely descriptive view of the imagery model, the matrix is compatible with the pattern being due to what subjects understood the experimental task to be (e.g., that the task is to simulate as closely as possible what they believe would happen in a situation in which they were looking at a real display). Summarizing such a pattern of behavior is a perfectly legitimate goal for a theory, although it only provides what Chomsky calls a "descriptive" as opposed to an "explanatory" theory. Even in this case *some* mechanisms might have to be assumed, for example mechanisms capable of representing beliefs, drawing inferences from them, generating representations of some intermediate states of the simulation as well as estimates of the relative times involved. What it would not require, however, are assumptions about the format in which the images are stored, displayed and accessed, since those properties would be doing no work here (the test being that the operative assumptions could be added to any model, regardless of the format it used for representing the relevant beliefs). It is clear from the writings of picture-theorists that this is *not* what they have in mind; rather they take this model to be what we have called a *model of the architecture* of mental imagery (certainly this is explicitly claimed in Kosslyn, 1981).

Let us first examine the "matrix model" (Kosslyn, 1994) viewed as an architectural model. Later I will consider whether the empirical facts are consistent with such a model. For now let us see why such a

model appears intuitively attractive and what in fact it assumes about the mental architecture underlying the use of mental imagery. The conclusion I will arrive at is that a matrix is attractive precisely because it *can* be (and typically is) viewed as a computer simulation of a real 2D surface, which is precisely the *literal* picture-in-the-head assumption one was trying to avoid by talking of “functional space.” Consider some reasons why a matrix appears to be like an image. It appears to have two dimensions, to explicitly *have* distances (if we identify distance with the number of cells lying between two cells), as opposed to merely representing them (say in some numerical code), and it appears to explicitly *have* empty spaces. It also seems that it can be “scanned” from one place to another, since there is a natural sense of the topological property of being “adjacent,” so that searching for an object by passing through intervening empty places makes sense. The trouble is that all these spatial notions – adjacency, distance, unfilled places and scanning – are properties of a way of thinking about a matrix; they are not properties of the matrix data structure itself. There is nothing “adjacent” between cell (25, 43) and cell (25, 44) except when we view them as points in a real space as opposed to two quite discrete registers in the computer, which is what they are. What we think of quite naturally as two *locations* in space are nothing but two discrete symbols or register names. What makes them appear to be locations is not inherent in their being a matrix data structure. According to Kosslyn, “it is only by virtue of how this information is ‘read’ and processed that it comes to function as if it were arranged into an array (with some points being close, some far, some falling along a diagonal, and so on).” But that isn’t the way a matrix has to be *used unless it is being used to simulate a real spatial surface or display* and then it is not the matrix but the thing being simulated that has the spatial properties. In a matrix, one does not get to a particular cell by “moving” there from an “adjacent” cell – one simply retrieves the contents of the cell given its name (names happen to be pairs of symbols, but that is of no consequence – the pairs are converted to a single address anyway). Of course when it is used as a model of mental imagery, accessing registers is constrained in the way stipulated by the theory, viz, one gets to a cell by accessing a sequence of cells defined as being between the currently accessed cell and the desired cell. But then it is this extrinsically stipulated constraint that is responsible for the behavior, not the fact that it is a matrix, and the reason the extrinsic constraint is stipulated is because the theorist believes that the image is actually written on a physical surface! This, it seems to me, is the only possible motivation for what would otherwise be a totally arbitrary constraint.

The notion of a functional space has no explanatory function in this context because a functional space has whatever properties we require it to have. If we wish the functional space to have the properties of real space why then we arrange for the relevant properties to be manifested. But then we cannot appeal to something we call a functional space to explain why it has certain properties: It has those properties because we stipulated them. The spatiality of a matrix (or any other implementation of “functional space”) is something that is stipulated or assumed *in addition* to the computational properties of the data structure. The critical fact here is that such an extrinsic postulate could be applied to *any* theory of mental images, including one that assumes that images are sentence-like symbolic structures. Indeed, there is nothing to prevent us from modeling an image as a set of sentences in some logical calculus and then, in addition, stipulating that to go from one place (however such a place is referenced, including the use of numerals as names) to another place requires that we pass through “adjacent” places, where adjacency is defined in terms of the ordinal properties (or even metrical properties, if the evidence merits that assumption) of place names. If this sounds *ad hoc*, that’s because it is *ad hoc*! But it is no more *ad hoc* than it is when applied to a matrix formalism. For example, in a matrix data structure it is just as natural to go from one “place” to *any* other place (think of places as having names, you can go from a place named Q1 to a place named Q2 just by issuing those two names to the function that accesses cells in a matrix). If you want to restrict the movement you have to do it by assuming a constraint that is extrinsic to the form of the matrix. It is only if you view the matrix as a representation of a real (physical) two-dimensional display that you get a notion of “adjacent cell,” and it is only if you confine operations on names to ones that move to adjacent cells defined in this manner, rather than to other cells, that you get a notion of scanning. The same is true of the claim that matrices represent empty places. An empty place is just a variable name with no value: Any form of computational model can make the assumption that there are names for unoccupied places (in fact you don’t even have to assume that these places exist prior to your making an inquiry about their contents – as they don’t in some implementations of sparse matrices).

The point here is not that a matrix representation is wrong. It's just that it is neutral with respect to the question of whether it is supposed to be a model of an intrinsic property of mental images – the property that is responsible for the many experimental results such as scanning – or whether it is supposed to be a way of summarizing the data which actually arise from people's knowledge of how things happen in the world (i.e., that when using mental images people usually act as though they are observing things in the world). When appeal to the matrix appears to provide a natural and principled account of the spatial imagery phenomena (such as scanning and the effect of image size) it is invariably because the theorist is viewing it as a representation of a real two-dimensional surface. In other words, the theory assumes the existence of a real surface. A real two-dimensional surface *has* the relevant properties because of the physical properties of the medium. For example, on a real physical surface it takes time $t = d / v$ to traverse a distance d at velocity v and this is guaranteed by a law of nature. In a "functional" space the relation between d , v , and t is indeterminate: It has to be stipulated in terms of extrinsic constraints. In a real physical surface the relative 2D distances among points remains fixed over certain kinds of transformations (e.g., rotation, translation, size change) and the Euclidean axioms hold of distances between them. In particular, if something is a distance then it must at the very least obey metrical axioms; for example the triangle inequality must hold of the distances d among three elements x , y , and z so that $d(x,y) + d(y,z) = d(x,z)$. In a functional space none of these constraints is required to hold by virtue of the format or intrinsic nature of the representation (unless, once again, functional space is just a gloss for real space).

Of course it is possible, in principle, to implement a model of space in another (analogue) medium by mapping sets of properties of space onto certain properties of the medium (that's what an analogue computer typically does). For example, one might use the relationship among voltage, resistance and current flow to model the relationship between distance, speed and time, respectively. In that case the constraints on properties of the model would once again be intrinsic – certain properties and relations would hold because of the physics of the analogue medium. This would constitute an analogue model of the system consisting of those three properties. But it would be surprising if *all* properties of space could be modeled by something other than space itself. Notice that an analogue model of distance, speed and time would fail to model lots of other aspects of space and motion such as the principles that hold among distances and relative directions, or distances and areas. It would fail to model Pythagoras' Theorem, the invariance of some relations (like relative distances and angles) over certain transformations (such as rotation), and certainly not such assumed image properties as the visibility of an object's features as a function of the size of the object. It might be possible to motivate properties such as visibility as a function of size, but only if we are talking about real size, not size in some "functional space." There are an unlimited number of such properties and relationships, which is why it's hard to think of any system of variables other than those intrinsic to space and time that could model it. The problem of finding a non-Cartesian model of Euclidean space is precisely what concerned Jean Nicod. His beginnings on this problem (Nicod, 1970), though brilliant in itself, did not go very far towards providing possible models of space that could be of use in understanding mental imagery.

But this may all be irrelevant to the issue of the nature of mental images. The real question is not how to find an analogue representation of space, but whether one *should* model properties of space in modeling the architecture of mental imagery. My purpose in belaboring the above points about what constraints the matrix format imposes and what constraints are imposed by extrinsic stipulated assumptions is simply to set the stage for the real issue, which is the empirical one. I have already described some of the empirical findings earlier (e.g., our own studies of mental scanning when the task was understood as imagining lights that go off in one place and simultaneously go on at another place, or in which the task focused on aspects of retrieving information from an image that play down the question of how one gets from one place to another). The same goes for the finding that it takes longer to answer questions about small visual details when the object is viewed as "large" than when it is viewed as "small." The way the data turn out in these cases strongly suggests that the mind does not work as though the imagery architecture imposes constraints

like those you would expect of a real spatial display,⁵⁴ at least not in the case of the phenomena discussed in Chapter 6. It appears that we are not *required* to scan through adjacent places in getting from one place to another in an image: We can get there as quickly or as slowly as we wish, with or without visiting intermediate (empty or filled) places. In fact as mentioned earlier, some of our recent work provides reason to doubt that we *can* smoothly scan a mental image (or even a real scene) or visit more than a few places along the way, even if we wanted to. Rather it looks as though the best we can do visually is estimate how long it would take an object traveling at a given speed to move between a few places we can see, and the best we can do in our mental image is to imagine *that an object is moving*, but not to imagine the object as being at a succession of intermediate places along the way (at least not more for than a few such places). Since the spatial nature of mental images is such a well-entrenched believe, however, I will devote the next section to discuss what it would mean for images to be spatial and also to briefly discuss two potential reasons why in certain situations images may actually exhibit some nontrivial spatial properties without themselves being laid out on a spatial surface.

7.2 Why do we think that images are *spatial*?

7.2.1 Physical properties of mental states: crossing levels of explanation

In chapter 1 I mentioned the great temptation to reify experiential properties like color or shape or duration. This tempting mistake (referred to in philosophy as “the intentional error”) is the one that slips from saying that you have an image of a scene and that the scene has property P, to the conclusion that the mental event or the formal object in your head itself *has* property P. The temptation is to equivocate between the two ambiguous senses of the phrase “an image of X with property P”; namely “an image of (X which has property P)” and “(an image of X) which has property P.” In the first case it is X, the thing in the world, that has the property, whereas in the second case it is the image of X, a thing in the head, which is claimed to have the property. In referring to one’s representational states (e.g., one’s thoughts or images) the relevant properties are always properties of the thing one is imagining, not of the object that stands in for it – of the representation itself. The degree of the temptation to reify properties varies with the particular property. It is pretty easy to see that an image of a cat does not have to be furry, an image of an orange need not be colored orange, or that an image of one object on top of another need not be made up of parts that themselves are on top of other parts of the image; but it is a bit harder to accept that an image of a big thing need not be large (or larger than an image of a small thing), and harder still to appreciate that imagining a long-lasting event need not last long.

I once wrote a brief commentary (Pylyshyn, 1979a) in which I reflected on how freely we speak of the beginning, end and duration of mental events – for example, of the representations produced by perception or by imagination. I wondered why we were not disposed to speak of other physical properties of mental events, such as their temperature or mass or color. After all, these are all legitimate physical properties: If the result of perception is a physical state or event, which few people would deny, then why do we find it odd to ask what color or weight or temperature a percept is, somewhat less odd to ask how big it is or where it is, but are quite at ease in asking how long it took. The commentary did not elicit any response – people found it puzzling why I should even raise such a question when it is obvious that mental events have durations but not temperatures. But this should have been a puzzle. The reason we do not speak of the physical properties of mental events is not because we are closet dualists who believe that mental things are

⁵⁴ But are the properties of space cognitively penetrable? Can we imagine space not having the properties it has? (Kosslyn et al., 1979) claims that the spatial property of the image display constrains what we can imagine. He says (p549), “We predict that this component will not allow cognitive penetration: that a person’s knowledge, beliefs, intentions, and so on, will not alter the spatial structure that we believe the display has. Thus we predict that a person cannot at will make his surface display four dimensional or non-Euclidean...” But as we remarked at the beginning of Chapter 6, the more likely reason why people cannot image a four-dimensional or non-Euclidean world is that they do not know what such a world would *look like* and knowing what it would look like is essential to being able to carry out the task we call “imaging.” According to this view, not knowing where the edges and shadows will fall is alone sufficient reason for failing to image it without any need to invoke properties of a “surface display.”

in a different realm than physical things (as Descartes did), but because mental event *types* need not correspond to physical event *types*. To speak of an event type is to refer to an entire class of events among which we make no distinction for certain purposes. All the instances of the letter “a” on this page are considered equivalent for the purposes of reading, even though they may differ in size, font, and in other minute ways of interest to a typesetter – and they certainly differ in their location. Thus we speak of the letter *type* “a” of which there are many letter *tokens* or instances of “a” on the page that are distinguishable in many different ways. There is no answer to the question; What size is the letter “a,” because it can be any size and still be the letter “a.” But a mental event type has many event tokens each of which could have arbitrarily different physical properties – at least they are not required to have any fixed property merely by virtue of being a member of a particular event type. When we ask whether a mental event (such as imagining a melody being played) has a particular duration, we are asking about the event-type, not the event-token. There need be no answer to the question: “What is the temperature of an imagining of the singing of *Happy Birthday*,” though there is an answer to the question, “How many words are there in an imagining of the singing of *Happy Birthday*” (at least according to a certain interpretation of what it means to “imagine”)⁵⁵. Similarly there need be no answer to the question about its size or its duration.

To make the idea of an event-type more concrete, consider the parallel case in computing. The event of computing a certain function (say a square root function) is realized physically in a computer; therefore it is a physical event – no doubt about that. Yet *where* it is carried out it is not relevant to its being that particular function because it may occur anywhere and certainly will occur over widely dispersed locations from occasion to occasion. There is no physical location corresponding to the function *as such*, even though each token occurrence of such a function does take place somewhere or other. This is what we mean by an event type: it is what all occasions of the event (e.g. executing a square root function) have in common. Clearly all events of executing the square root have certain functional properties in common (namely, they all map 4 into 2, 9 into 3, 16 into 4, and so on). But is there a temperature corresponding the square root function? Perhaps. Nothing in principle prohibits all possible instances of executing a square root from being realized in some physical form that always has a certain temperature, though that would certainly be surprising (inasmuch as it is not necessary that the instances share some common temperature property – it is not hard to imagine one that doesn’t just by putting the computer in a freezer!). And even if there was such a property, it is highly unlikely to be of computational significance. The point is that the function is defined and has its significance in the arena of mathematical operations, not in the arena of physical processes and the two are not type-equivalent. Now what about time: Does the square root function have a duration? The same answer applies. It does if every token occasion on which it occurs takes the same amount of time (within some limits). If the duration varies from occasion to occasion then only token computations of that function have some particular duration, the function type does not. This is what I said about the duration of mental events. The response my comment evoked (“most people think that mental events have durations but Pylyshyn does not”) shows how deeply the reification of time goes. The interesting thing about this reaction is not that people think it makes sense to speak of the duration of a mental event (it does, for tokens of the event), but that the intentional error is so deep that people do not notice that any assumption is being made.

If there is a temptation to reify time in the representation of temporally extended events, the temptation to reify space is at least as strong and has immediate implications for one’s theory of mental imagery. The temptation to assume an inner display is linked to the fact that images are experienced as distributed in space (just as they are experienced as distributed in time). Because they are experienced as distributed in space we find it natural to believe that there are “places” on the image – indeed it is nearly inconceivable that an image should fail to have distinct places on it. This leads naturally to the belief that there must be a medium where “places” have a real existence. We feel there must be a form of representation underlying an image such that it makes sense to ask of some object X in the image: Where (in the image) is X? Or, How big is

⁵⁵ This is true if what one means by “imagine a singing of the song *Happy Birthday*” is that this entails imagining each individual word of the song. The assumption that this is generally what people mean (and in particular, what subjects in psychological experiments think the experimenter means) by the phrase “imagine event X” is discussed in Section 6.3.2.

(the image of) X? Or, How are X's parts located (in the image) relative to one another? If the space in question were not real, then in what sense could we ask where a particular feature is located in relation to other features? Moreover, we have seen that a feature's being at a particular place in relation to other features in a scene *does* have an effect on how the scene is perceived. We saw this in the examples given in Chapter 1. It is the fact that the illusory line is seen to be (or represented as being) in a certain place that creates the Pogendorff illusion, illustrated in Figure 1-5 of Chapter 1. Dan Dennett (Dennett, 1991) has written on the temptation to reify mental space and time and has pointed out, correctly in my view, that to represent a certain spatial pattern does not require that one represent all its distinct parts as individual elements separated in space. For example in representing a checkerboard one need not represent each of its squares at each possible location on the board (as assumed when one speaks of the image of the checkerboard being laid out in functional space). Dennett suggested that rather than explicitly representing each part of the imagined scene and each feature of the scene at once, the visual system may be just assigning coarse labels to regions ("more of the same here"). But this leaves a puzzle: Where is "here" and where is the coarse label placed, if not on the dubious inner display? Certainly "here" does not refer to a place on the retina or on the objects in the world (unless we are going around putting real labels on things!). The idea of labeling parts of a scene is ubiquitous and plays an important role in computational theories of vision, as we saw in Chapter 3 (especially in 3.1.1.1). But what is it that is being labeled? Can we label part of a representation or part of an experience? Many psychological theories of pattern detection (Ullman, 1984) and of visual attention (Watson & Humphreys, 1997; Yantis & Jones, 1991) speak of placing "tags" on certain stimulus objects (for example, to tell us that the item has already been processed, as in counting). If the tags must be located at a precise location in the representation, then such theories must tacitly assume an inner display of some sort – or at least a representation in which it makes sense to refer to distinct *locations*. Is there any sense that can be made of talk of labeling or of tagging places in a scene that does not assume an inner image that reifies space?

Space has been subject to a great deal of analysis long before the debate over the nature of mental images surfaced in cognitive science. Space has always been viewed as a sort of receptacle that contains matter without itself partaking in the laws of nature – a view that had to be abandoned with the acceptance of general relativity and the notion of curved space. Even with this change in status, space (along with time) retained its special place among properties. Emmanuel Kant claimed that our intuitions of space and time were prior to our concepts of properties – that they were *a priori* categories of mind, presumably preconceptual and innate. The French mathematician, (Pointcaré, 1963), taking a more empirical stance, wondered (and provided a partial answer to) the question how we could ever learn that space has three dimensions, given our multidimensional and multimodal experience of it. And more recently a brilliant young French graduate student named Jean Nicod, wrote a dissertation speculating on how we could construct a three-dimensional world from the sensory experiences available to us (Nicod, 1970). He put the problem differently. He took space itself to be a set of formal properties defined (roughly) by the axioms of Euclidean geometry and asked how the mind could develop a model of these axioms based on sensory experiences, together with a small number of basic perceptual categories (primarily the notion of volumetric containment). Nicod's starting point was the one we must take seriously. To say that something is spatial is to claim that it instantiates (or is a model of) the Euclidean axioms of plane geometry, at least in some approximate way (perhaps the model might be what is sometimes referred to as "locally Euclidean"). In addition, in speaking of something being spatial one usually implies that it is also metrical (or quantitative), which means that certain of its properties also fall under the metric axioms⁵⁶ (see, for example, Luce, D'Zmura, Hoffman, Iverson, & Romney, 1995; Palmer, 1978). Thus a rigorous way to think of the claim that images are spatial is as the claim that certain properties of images (not of *what* they represent, but of their inherent *form* or their material instantiation) can be mapped onto, or fall under, a variety of formal mathematical axioms.

⁵⁶ In most formulations there are 4 metric axioms: If d is a metric (distance) measure then: (1) $d(x,y) = 0$; (2) If $d(x,y)=0$ then $x = y$; (3) $d(x,y) = d(y,x)$; and (4) $d(x,z) = d(x,y)+d(y,z)$.

The claim that mental images have spatial properties in this formal sense is clearly much stronger than the empirical facts warrant. Indeed, even visually-perceived space is not Euclidean because it fails to meet many Euclidean requirements (Attneave, 1954; Luce et al., 1995; Suppes, 1995; Todd, Tittle & Norman, 1995). What exactly one means by images having spatial properties is thus not very clear. Nonetheless there are some properties of imagery that most writers have in mind when they claim that images are spatial. Before I examine the possibility that images may actually be displayed on a real physical surface in the brain, I should stop to ask what reasons there are (other than the pervasive temptation to reify mental qualities discussed above) for thinking that some form of space may be involved in the representation of spatial properties of the world in mental imagery. There are obviously many reasons for thinking that mental images at least *encode* metrical spatial properties in some way. For example, distances on an image appear to map onto distance on the represented world in a systematic (and monotonic) way: people are able to make judgments of relative size and even some (limited) absolute judgments of size from their experienced images (Miller, 1956; Shiffrin & Nosofsky, 1994). Even if one agrees with the analysis I provided in Chapter 6, attributing the scanning effect to a mental simulation of what would happen in the real situation, this still requires that relative distances be encoded and used in the simulation. The ability to represent relative spatial magnitudes is surely a necessary part of our ability to recall and reason about geometrical shapes, since shape is defined in terms of relative spatial dimensions. Consequently it is reasonable to think that we use some encoding of spatial magnitudes when engaged in entertaining mental images. Spatial intuitions are very powerful and appear, at least *prima facie*, to be operative when we reason about space while relying on our mental images, just as they are when we reason with the aid of a diagram (see chapter 8, section 8.3). If we are to shun the intuitively satisfying notion that we do this by drawing an inner picture, we will need some account of how we solve such problems at all. Nobody is yet in a position to provide a detailed account of this sort. On the other hand, neither are the proponents of the picture-theory: Even if there were real 2D diagrams in the head we have no idea how they could be used. What we do know is that sooner or later the pictorial information has to be interpreted and transformed into a form that can enter into inferences, i.e., a form that meets the requirements of compositionality and productivity discussed in Chapter 8, section 8.2 (and taken up in detail in Fodor, 1975; Fodor & Pylyshyn, 1988).

There are other properties of images that give them their apparent spatiality. Among these are the experiments discussed earlier (e.g., mental scanning), the more robust of which are those in which people “project” their image onto the world they are perceiving. They are discussed in the next section, where I suggest that some spatial properties inferred from imagery experiments are real, but do not arise from the spatial nature of the images themselves. These spatial properties, I argue, can be attributed to the real spatial nature of the sensory world onto which they are “projected.” Another source of evidence for the spatial nature of images comes from the way that images connect with the visuomotor system. These two sources of evidence for the spatiality of images are discussed in the following sections.

7.2.2 Inheritance of spatial properties of images from perceived space

In many imagery studies subjects are asked to imagine something while looking at a scene, thus at least phenomenologically superimposing or projecting an image onto the perceived world. Although it has been amply demonstrated (O'Regan & Lévy-Schoen, 1983) that true superposition of visual percepts does not occur when brief visual displays are presented in sequence, or across saccades, the impression that superposition occurs in cases of imagery remains strong. What happens, then, when a mental image (whether constructed or derived from memory) is superimposed on a scene? In many of these cases (e.g., Farah, 1989; Hayes, 1973; Podgorny & Shepard, 1978) a plausible answer is that one allocates attention to the scene according to a pattern guided by what is experienced as the projected image. A simpler way of putting this is that one simply *thinks* of imagined objects as being located in the same places as certain perceived ones. For example, in the (Podgorny & Shepard, 1978) study the investigators asked subjects to imagine a letter-like figure projected onto a grid, such as shown in Figure 7-1) and to indicate as quickly as possible whether a spot that was then displayed in the grid was located on or beside the imagined figure. In the visual version of the task, subjects were faster when the spot was on the figure than when it was

immediately beside it, faster when it was at certain stroke intersections (such as in the corners or the T junction) than when it was in the middle of a row or column, and so on. When subjects were asked to imagine the figure projected onto the empty grid, the pattern of reaction times obtained was very similar to the one obtained from the corresponding real display. This result was taken as suggesting that the visual system is involved in both the visual and the imaginal cases. But a more parsimonious account is that in “imagining” the figure in this task, observers merely attended to the rows and columns in which the imagined figure would have appeared. We know that people can indeed direct their attention to several objects in a display or to conform their attention to a particular shape. As I argued in (Pylyshyn, 1989), focusing attention in this way is all that is needed in order to generate the observed pattern of reaction times. In fact using displays similar to those used in the (Podgorny & Shepard, 1978) study but examining the threshold for detecting spots of light, (Farah, 1989) showed that the instruction to simply *attend* to certain regions was more effective in enhancing detection in those regions than the instruction to superimpose an image over the region.

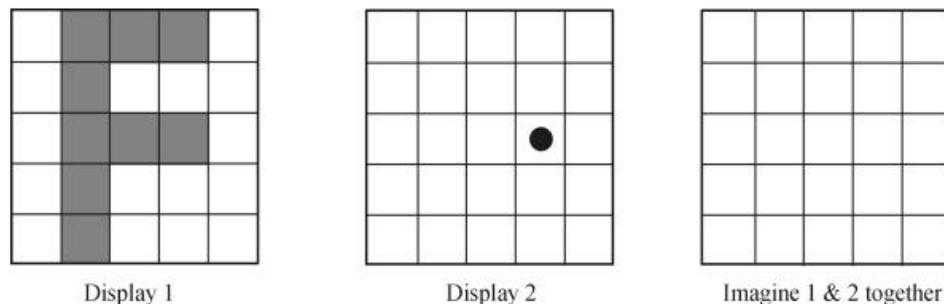


Figure 7-1. Observers were shown a figure (display 1) which they then had to retain as an image and to indicate whether the dot (display 2) occurred on or off the imagined figure. The pattern of reaction times was found to be similar to that observed when the figure was actually present. (based on Podgorny & Shepard, 1978).

A similar analysis applies in the case of other tasks that involve responding to image properties when images are superimposed over a perceived scene. If, for example, you imagine the map used to study mental scanning (discussed in Chapter 6) superimposed over one of the walls in the room you are in, you can use the visual features of the wall to anchor various objects in the imagined map. In this case, the increase in time it takes to access information from loci that are further apart is easily explained since the “images” or, more neutrally “thoughts,” of these objects *are actually* located further apart. What is special about such superposition cases is this: The world being viewed contains rigid 2D surfaces which embody the properties expressed by spatial axioms – i.e., Euclidean and other mathematical properties of metrical space literally apply to it – so the combined image/perception inherits these properties. How does this happen? How does cognition obtain access to these spatial properties and apply them to the superimposed image?

What makes it possible for certain spatial properties to be inherited from a real scene is the visual indexing mechanism discussed in chapter 5. Using this mechanism, a person can pick out a small number of objects in a scene and associated thoughts about particular objects with them. So, for example, the person could think that particular token objects in a scene correspond to certain imagined objects in memory. As we saw in Chapter 5 we can have thoughts such as “assume that this *<object-token-1>* is the beach, and that *<object-token-2>* is the lighthouse,” where the italicized terms are pointers to visual objects that are picked out and referenced using visual indexes. We have already seen that such visual indexes allow thoughts about certain token properties to be connected to particular objects in a scene the way that demonstrative terms, like “this” or “that” do in natural language. Thus we can literally think, “*this* is the beach,” “*this* is the lighthouse,” and so on. Given this capability, now something interesting happens. Because the scene obeys physical and geometrical laws, the spatial relations among indexed objects also systematically maintain their interrelations, providing only that visual indexes remain bound to their scene objects. For example, if you indexed three points that just happened to be collinear, then regardless of what

you believed about their relationship, they would always have an ordinal position along the line; the second point would have the relation “between” to the other two, and so on. So if you subsequently *noticed* that they were collinear or the “between” relation that held among the three points, you would be guaranteed that it was consistent with the axioms of geometry, whether or not you remembered or noticed that the points you had picked out had other properties and whether or not you knew that they maintained their fixed locations while you noticed new properties of their configuration. Such a guarantee would be underwritten, not by *your knowledge* of geometry (and, in particular, not by your knowledge of the formal properties of the relation “between”), but by the physical facts about the world you are looking at and the fact that your visual system could detect certain relations that hold among objects in that world. In other words, by picking out certain objects in the world whose locations are roughly where you believe or remember certain objects you are thinking about to be, and by binding objects of thought to these objects in the world, you are able to draw conclusions about their configuration by *visually* noticing these properties. Without such a display you would have to draw inferences based on the postulates of geometry.

This point connects directly with several of the phenomena that have been cited in support of the claim that mental images are spatial. For example, if you could individuate and refer to several objects in a visual scene and you could associate certain objects in the memorized map with each of these perceived objects (as suggested above) then you could literally scan your attention (or even your gaze) from one to another of these places. Thus the mental scanning phenomenon discussed in section 6.3.2.1 (viz., that it takes longer to scan attention between two points in an image when they are further away) becomes a *visual* scanning phenomenon since in that case you would be moving your attention *from one (real) place in the scene to another*, and that would require time roughly proportional to their (real) distance apart.⁵⁷ Similarly for other phenomena that may be attributed to attentional distribution over real scenes, such as those that might be responsible for certain visual illusions (as suggested in section 6.5.2). While one *could* think of this as equivalent to superimposing an image over the scene, there is a much simpler and more plausible way to view these imagery-induced phenomena. For example, in the scanning case all you need to be able to do is recall (from *some* representation of the scene) how far and in what direction point B is from point A in the situation you are imagining. Then you need to find an object in the scene that is roughly the same (relative) distance away from the A reference point, assign an index to that object, and think of the imaged object B as being located at that particular real indexed object. No “pictorial” information need be involved, just some relative distance representation (which may itself be symbolic or analogue, but not pictorial or spatial). In this way by anchoring a small number of imagined objects to real objects in the world, the imaginal world inherits the geometry of the real world.

7.2.2.1 Scanning when no surface is visible

What if the scanning experiment were to be carried out in the dark so that there were no visible objects to put into correspondence with the objects in your memory? One prediction would be that you would have trouble with this task, since it is known that after a few minutes of looking at such a display (called a Ganzfeld), vision becomes very unstable and it even becomes difficult to keep track of where you are looking in relation to where you were looking earlier (Avant, 1965). Such featureless displays are very rare – almost any surface has texture features, as can easily be seen, for example, in first and second derivative images which show potential edges (e.g., in Marr, 1982). But what if you generate a new image of something without at the same time viewing a real scene? What if you imagine a scene with your eyes closed? The first thing that can be said is that the results in such cases are much less robust and more easily influenced by task strategies and beliefs. It is not even clear that mental scanning experiments can be carried out in total darkness (for more than a very short time) since even viewing a single light in total darkness leads to instabilities such as the induced motion of the autokinetic effect (wherein the light appears

⁵⁷ The question arises what scanning speed we might expect of this type of scan. Saccadic eye movements are much faster than the observed mental scanning times so it is unlikely that the observed reaction times reflect actual saccades. The scanning time might, however, reflect a sequence of imaginings of some moving spot being first *here* then *here* and so on, where the demonstratives are bound to objects or texture elements along the way (as discussed in the research described in section 6.5.3).

to move around). As argued earlier (in section 6.5.4) there is some reason to believe that smooth imaginal scanning, in which the focus of the scan passes through intermediate points, is not possible under these conditions. Notwithstanding these problems, it may still be possible to generate the relevant time-distance relationships without having a spatially laid out scene either in the visible world or in your head. All you need is a way to represent distances. While there is no general theory of how such magnitudes are encoded, we know that they are encoded, not only in humans but also in animals (Gallistel, 1990). Notice that being able to encode magnitudes is quite different from the assumption of a spatial image, since analogue encoding schemes lack the multi-dimensionality and other properties of images⁵⁸.

This brings us to the one published study of mental scanning that did not involve a visual display. In this study by (Pinker et al., 1984), locations of objects in a 2D matrix were described verbally to subjects, along with the location and direction of an arrow. This task requires that subjects represent the position of three objects as well as the position and direction of an arrow, all based on a verbal description. In this experiment, as in the studies that used superimposed images, the task of determining whether the arrow pointed to one of the points took longer when the points were further away from the location of the arrow. From this the authors argued that the distance effect could not have been due to a visual scanning of the real scene, and therefore that image-scanning must be a constraint of the imagery system (or the architecture of the image representation system). It's true that such findings rule out literal scanning of the visual scene, but they still do not require a spatial medium of representation. As I noted above, one has to distinguish between *being able to encode information about distance* and having this information *in the form of a spatial display*. The Pinker et al study shows that people can recall locations in a way that reflects their relative metrical distances (at least in a coarse way) and that they can use this relative-location representation in the course of solving certain geometrical tasks. The fact that it took longer when the imagined distance between the arrow and the dots was greater shows that subjects were able to simulate the scanning situation without benefit of a perceived scene, but it does not show that greater distances in the imagined situation were represented by greater distances in the representation.

But why should it take longer to judge whether an arrow is pointing at an object in memory when the object is imagined to be further away? I have already considered some possible reasons for this pattern of results (see section 6.3.4), but it is important to recognize that there is so far no general answer to that question – whether or not you believe that images are stored in the form of pictures. All we can do is compare the plausibility of one or another *post hoc* account. The intuitive answer is that when the arrow and the point are further from one another it takes longer to draw a line from the arrow to the dot. But this sort of extrapolation is appropriate (and perhaps mandatory) *only* for real displays in which real lines are drawn from one point to another point (as opposed to, say, being laid down instantaneously). There is nothing we know about the mind that requires that in order to judge collinearity, a line must be drawn out from the arrow, since for anything but a real surface the operation of “drawing” is only a metaphor. To postulate such an operation in the case of a mental process is to rely on the assumed rigidity of (and the ability to write to) an imagery medium – the very assumption that we have been questioning. What we *can* assume about the mental process without begging the question of what images are like is that in imagining the process of solving the problem we go through a sequence of intermediate representations involving increasingly longer lines. Perhaps, as suggested earlier, we do so in order to simulate the process of drawing a line on a real surface, because extrapolating the arrow is what the real-world task that we are imagining would have required. The most natural (and accurate) way of determining whether a point would fall on the extension of an arrow is to extend a line from the arrow and see whether the line would collide with the

⁵⁸ Note that I have no quarrel with those who propose analogue representations of magnitudes. This is a very different matter from the assumption that there is an analogue for an entire system of magnitudes corresponding to space. The trouble is that unlike the hydraulic analogue of electric flow, an analogue of space would have to encompass many properties (and at least 4 dimensions) and meet a large number of constraints, such as those embodied in Euclidean axioms. It would have to exhibit such general properties as Pythagoras' Theorem, the single point-of-view requirement discussed in (Pinker & Finke, 1980) and countless other properties of projective geometry (including the metrical axioms, see section 7.1). It is no wonder that nobody has been able to think of an analogue to space-time other than space-time itself.

point. So in imagining this particular natural solution, subjects carry out in their mind precisely what they would have had to carry out on paper, imagining some (though not necessarily all) of the intermediate states of this drawing process.

The line-extrapolation solution to the problem in the real situation is dictated by properties of the rigid surface, by facts about geometry, by the meaning of “pointing to,” and by the available operations (e.g., being able to draw or to lay down a ruler). What is different about the imagined case is that none of these determiners of the solution process apply. The mental task does not require that a line be drawn, and furthermore no literal line *is* in fact drawn. All that happens is that in imagining the process of solving the problem the person imagines a sequence of increasingly longer lines emanating from the arrow. Now here is the important difference between imagining the process and actually carrying it out: Because the line is not a literal object and the drawing is not an actual extrapolation of a line (laying down of pigment or a ruler on a rigid surface) this sequence of imaginings cannot in itself solve the problem. All it can do is simulate a sequence of representations of events corresponding to what would have been seen if the line-drawing process had been carried out on a real surface. Subjective impressions notwithstanding, whether such a line would or would not terminate at one of the dots cannot be determined by “noticing” this on the image. Whether or not such an imagined sequence eventuates in the imagined line intersecting a dot is not something that merely happens as a law of nature, the way it would if you were drawing the line on a piece of paper. So how *is* the problem solved mentally? As far as I know nobody has even asked the question in the appropriate way, so seductive is our internalization of the physical solution. Both the problem of representing space (and more generally, of representing a system of magnitudes) and the problem of reasoning about spatial relations are poorly understood, despite the fact that it is known that many animal species are extremely good at it (see, e.g., Gallistel, 1990, who also provides a strong argument that humans and animals may represent magnitudes by storing analogue quantities in a “accumulator”). Although in certain contexts humans have an extremely accurate representation of magnitudes (as show, for example, by their ability to navigate and to exhibit ballistic control of motor movements), these representations tend to be contained within specialized motor-control modules. When it comes to recalling magnitudes, say in making “absolute judgments,” people are extremely poor.

A far more reasonable assumption, discussed in the next section, is that we are able to exploit not only visible space in carrying out mental scanning (as discussed above), but also a more general “spatial sense” which may involve proprioceptively sensed space or the space potential motor movements (see also section 3.2.1.3).

7.3 The exploitation of proprioceptive or motor space

Where does the strong impression of the spatial nature of our images come from? What, other than the subjective experience of space, prompt us to believe that images are in some important sense spatial? One simple answer is that when we imagine spatially distributed layout of objects and shapes then something is indeed spatial, namely the layouts and shapes that we are imagining. It is the things that we think about, not the patterns in our brain that we think with, that are spatial. This simple answer should carry more persuasive force than it typically does: just as when we imagine a round thing, or a green thing, or a furry thing, it is the thing we are imagining that has those properties, not our image. But here is one difference in the case of mental images: If you close your eyes and imagine a familiar spatial layout (say a map of your city), you feel the image is “out there in front of you” in the sense that you can actually point to parts of it. But what are you actually pointing at when you do this? I have already suggested that when you do this while looking at a scene (“projecting” your image onto the visible world) you may be binding objects in your image to objects in the scene, thus providing the imagined objects with an actual location in the world, and thereby inheriting the spatial properties of the real external space. Might it be that when you do this with eyes shut (or in the dark) you bind objects in your image to places in a *proprioceptively sensed* space? If that were so then there would once again be a real space over which scanning could occur (assuming that the scanning result is not just a consequence of the demand of the task of simulating seeing the map, and also assuming that it is possible to scan across empty space, both of which are in serious doubt as we have seen) but once again it would not be in the head; it would be real space in the world or in the body, sensed through proprioception, audition or any other active sensory system that was operating when eyes are closed.

Our sense of space is extremely well developed and is used not only for thinking of concrete spatial patterns, but also for individuating and thinking of abstract ideas. In fact, sign languages (like American Sign Language) makes use of locations in speaker-hearers’ share space to individuate ideas and refer back to them. An entire topic can be located at a place in space and then when the speaker wishes to refer to that topic he or she simply points to the empty space where the topic had been left. You can easily demonstrate for yourself how good we are at localizing things in the space around us. Close your eyes and point to things in the room around you; you may find that you can point accurately and without hesitation – even to things behind you. Given this skill it seems plausible that we can utilize it in the absence of vision for binding objects in our image to places in our immediate proprioceptive space. What this would give you is the sensed spatial quality of images without requiring the images to *have* space themselves. The difference between appealing to images (even proprioceptive images) and what I have been calling a *spatial sense*, is that the latter does not assume a spatial representation, only the skill to pick out locations that are currently being sensed, through proprioception, kinesthesia, audition, or whatever ambient inputs that are available that we can use to calibrate locations.

Studies of the recall of locations have empirically demonstrated the nature of the skill that allows one to sense where things are and also to retain where one has “placed” things in one’s imagination. For example, (Attneave & Farrar, 1977; Attneave & Pierce, 1978) showed that the ability to recall locations was extremely good and about the same whether the locations were in front of or behind the observer. For example, when observers looked at and learned the locations of 7 objects in front of them and later were seated with their backs to where the objects had been, they could recall the relative locations of these objects almost as well as they could if they were asked to imagine them being in front of them. In this case it appeared that observers could easily take at least one of two perspectives 180 degrees apart regarding the locations of objects in a room. They could do this even without generating a detailed visual image of the objects. (Attneave & Farrar, 1977) reported that when subjects were asked about the relative location of two objects “...the second object was located in space (subjects typically said) and the question was answered accordingly, before the object was clearly pictured. This is logically consistent with the report that images were evoked or constructed, rather than continuously present: one must decide *where* to draw the picture before drawing it.” It seems that deciding where the item is occurs primitively, quickly and accurately. Attneave & Farrar also report that when an image of the scene behind the subject’s head did

occur it was not accompanied by a sense of turning-and-looking. They remark, “This contradicts the view that a visual image must correspond to some possible visual input. ... We are being told, in effect, that the *mind's eye* has a cycloramic, 360 degree field.” The notion that representing location-in-space is rather different, both phenomenologically and behaviorally, from what we usually consider to be visual images (which have a “visual angle” about the size of real vision Kosslyn, 1978).

The study of the “sense of space” (a term chose so as not to prejudice the question of whether the space is visual, proprioceptive, motoric, or completely amodal) has only recently been conducted under controlled conditions and has led to some unexpected findings. For example, it has been found that although people do have a robust sense of the space around them, this space tends to be calibrated primarily with respect to where the person actually is located at any moment. The reference point where people perceive themselves as being depends on their motor activity; as they move about they automatically recalibrate their proprioceptive sense of space, even if they move about without benefit of vision. For example, (Rieser, Guth & Hill, 1986) had subjects view a set of target objects (which also served as alternative viewing points) and then had them either walk blindfolded to specified points or merely imagine walking to these points, and then to indicate (by pointing) the direction of other targets. They found that people were faster and more accurate when they had moved to the optional locations, even though they did not have the benefit of any visual information in doing so. This was also true for pure rotation. People who had rotated their body appeared to instantaneously recalibrate their orientation so they could point to the location of various targets, whereas when they merely imagined themselves to rotate, their localization of targets was slow and deliberate⁵⁹ (Farrell & Robertson, 1998; Rieser, 1989).

The idea that the spatial quality of a mental image derives from its connection with the proprioceptive and motor systems is further supported by the work of (Finke, 1979) on the interaction of mental images and visual-motor control and by findings regarding the interaction of motor activity in space and locations in mental images (e.g., the work by Tlauka & McKenna, 1998, on SR compatibility). This work was carried out to support the picture theory of mental imagery, but as we will see, it does not require that anything pictorial be involved; only the positions of objects in the image is relevant. For example, the SR compatibility findings of (Tlauka & McKenna, 1998) showed that when you respond using crossed and uncrossed hands, it takes longer to respond to features in the opposite side of the image. From this (Tlauka & McKenna, 1998) concluded that stimulus-response compatibility factors affect reactions to *locations in images* as well as in real displays. But in fact if what it means for something to be located in a certain place (“*there*”) in an image is nothing more than that in order to reach it you would need to reach towards (or orient towards) a particular location in proprioceptive space (“*there*” in a proprioceptive frame of reference), then the result is unsurprising: Whatever phenomena one finds when a display is located “out there” in front of on observer, should also be found when an imaging a layout in the same location.

The (Finke, 1979) studies are even more interesting in this regard because they involve a detailed analysis of the interaction of imagery and visual-motor coordination and “felt location” of objects. In a series of ingenious experiments, Ronald Finke found that the well-known adaptation to displacing prisms

⁵⁹ It is possible to make too much of the involvement of motor activity in mental imagery. I have suggested that we use our proprioceptive/motor space in deriving the spatial character of mental images. But others have suggested that the motor system is involved in transforming mental images as well. The role that motor mechanisms play in the transformation of visual images is far from clear, notwithstanding evidence of correlations between visual image transformations and activity in parts of the motor cortex (Cohen, Kosslyn, Breiter, DiGirolamo, Thompson, Anderson, Bookheimer, Rosen, & Belliveau, 1996; Richter, Somorjai, Summers, Jarmasz, Menon, Gati, Georgopoulos, Tegeler, Ugurbil, & Kim, 2000), or the influence of real motor actions on visual transformations (Wexler, Kosslyn & Berthoz, 1998). Some of the cortical activity observed during both motor performance and the mental transformation of visual images, may reflect the fact that these areas (e.g., posterior parietal cortex) compute some of the higher-level functions required for extrapolating trajectories, for tracking, for planning, and for visuomotor coordination (Anderson, Snyder, Bradley, & Xing, 1997). Since many of these functions also have to be computed in the course of anticipating movements visually, it is reasonable that the same areas might be active in both cases. While studying the interaction of imagery and the motor system is clearly important, at the present time we are far from justified in concluding that dynamic visual imagery is carried out *by means of* the motor system (or that visual operations *exploit* motor control mechanisms). This way of speaking suggests that our motor system can grasp and manipulate our images, a view that is unfortunately in keeping with the mental reification of the world that we find in much mental imagery theorizing.

could be obtained using imagery alone. These studies are of special interest to the present discussion because they illustrate the way in which projected images can work like real percepts in certain ways – in particular in respect to perceptual-motor connections. They also illustrate an important role played by visual indexes in accounting for certain results in studies on mental imagery. Because of this the studies will be described in some detail.

In one study, (Finke, 1979) asked subjects to imagine seeing their (hidden) hand to be in certain specified locations. The locations where he asked them to imagine their hand corresponded to the errors of displacement actually made by another subject who had worn displacing prisms. He found both the pattern of adaptation and the pattern of after-effects to be similar to those exhibited by subjects who actually wore displacing prisms. Now it is known that adaptation can occur to solely verbally presented error information (Kelso, Cook, Olson, & Epstein, 1975; Uhlarik, 1973), though in that cases (and in contrast with the case where the hand is continually viewed), the adaptation occurs more slowly and transfers completely to the nonadapted hand. Yet Finke found that in the case of imagined hand position, the adaptation, though significantly lower in magnitude, followed the pattern observed with the usual visual feedback of hand position. Moreover, when subjects were told that their hand was not where they imagined it to be, the adaptation effects was nonetheless governed by the imagined location, rather than where they were told their hand was, and followed the same pattern as that observed with both imagery and actual visually presented error information. When subjects did not move their arm, or if they just imagined moving their arm, the results were like those obtained when they were only given verbal feedback. From these results Finke concluded that adaptation to imagined hand location tapped into the visuomotor system at the same “level” as that of visually presented information. But do these results really require that we appeal to the visual system, as understood in chapter 2, or can they be explained in terms of the orienting of attention to *real* places in a visual display?

It seems that what is going on in prism adaptation experiments is a recalibration between where subjects are looking or visually attending and either where they feel their arm is located or the motor command they issued to move their arm (the so-called re-afferent signal). The exact way this happens has been the subject of some debate (Howard, 1982), but it is generally accepted that important factors include the discrepancy between the seen position and the felt position of the hand (or the discordance between visual and kinesthetic/proprioceptive location information). Significantly, such discordance does not require that the visual system recover any visual property of the hand other than its location. Indeed, in some studies of adaptation subjects viewed a point source of light attached to their hand rather than the hand itself (Mather & Lackner, 1977) with little decrement in adaptation. But where the subject attends is equally important (Canon, 1970, 1971). In some cases even an immobile hand can elicit adaptation providing the subject visually attends to it (Mather & Lackner, 1981). Thus the imagery condition in Finke’s study provides all that is needed for adaptation – without making any assumptions about the nature of imagery. Subjects direct their gaze towards a particular (erroneous) location where they are in effect told to pretend their hand is located, thus focusing attention on the discordance between this viewed location and their kinesthetic and proprioceptive sense of the position of their arm.⁶⁰

It seems that there are a number of imagery-motor phenomena that depend only on orienting one’s gaze or one’s focal attention to certain perceived locations. The Finke study of adaptation of reaching is a plausible example of this sort of phenomenon, as is the Tlauka & Mckenna study of S-R compatibility. None of these results require that imagery feed into the visuomotor system. Indeed, these two cases involve *actual* visual perception of location (i.e., there really are visual objects located in the relevant locations and

⁶⁰ Ian Howard (Howard, 1982) provides a thorough discussion of the conditions under which one gets more or less adaptation. The most important requirement is that the discordant information be salient for the subject and that it be attended to and interpreted as a discordance between two measures of the position of the same limb. Thus anything that focuses more attention on the discordance and produces greater conviction that something is awry helps strengthen the adaptation effect. It makes sense then that merely telling subjects where their hand is would not be expected to produce the same degree of effect as asking them to *pretend that it actually is* at a particular location, which is what imagery instructions do.

they are attended). Since the adaptation phenomena (as well as the S-R compatibility phenomena) do not require the form information provided by the projected mental images (over and above the location information provided visually), they do not in any way implicate the visual system in the processing of mental images.

Thus visuomotor evidence for the spatiality of images in fact provides support for our notion that the two are inextricably connected precisely because the spatiality of images derives directly from the spatiality of locations in proprioceptive and motor space. This connection of image locations with both proprioceptively sensed space and with potential actions of the motor system is much more important than has generally been recognized. It extends the earlier argument about imaginal space being inherited from vision to the inheritance of space from a wider range of space-sensing modalities. Just as we can scan our eyes or our attention in relation to the visual perceived space when we examine images that are projected into a visual scene, so we can move our hand from one imagined place to another, and when we do so we demonstrate the spatiality of images.

7.3.1 Visuomotor interaction with images

Finke and others have interpreted the findings of his adaptation experiments as showing that imagery feeds back into the motor system just the way that vision does. But do images engage the motor system the same way that vision does? According to the account I have been giving, the only thing that engages the motor system are the locations of imagined objects in proprioceptive or motor space (and they do so trivially because that's what the location of objects in an image *means*). A more interesting question is whether anything more than location is involved when images interact with the motor system.

When we look in detail at cases that involve more than just the location of imagined objects, we find that images do not interact with the perceptual motor system in a way that is characteristic of visual interaction with that system. To show this we need to look at certain signature properties of the visual control of movements, rather than at cases where the control may actually be mediated only by spatial attention. One clear example of strictly visual control of motor action is smooth pursuit. People can track the motion of slowly moving objects with a characteristic sort of eye movement called *smooth pursuit*. There are also reports that under certain circumstances people can track the voluntary (and perhaps even involuntary) movement of their hand in the dark (Mather & Lackner, 1980). They can also track the motion of objects that are partially hidden from view (Steinbach, 1976), and even of induced (apparent) motion of a point produced by a moving frame surrounding the point (Wyatt & Pola, 1979). In other words they can smoothly pursue inputs generated by the early vision system. Yet what people cannot do is smoothly pursue the movement of imagined objects. In fact it appears to be impossible to voluntarily initiate smooth pursuit tracking without a moving stimulus (Kowler, 1990).

Another example of a characteristic visual control is reaching to grasp a visible object. Although we can in some sense reach out to grasp imagined objects, when we do so we are essentially *pantomiming* a reaching movement rather than engaging the visuomotor system. The latter exhibits certain quite specific trajectory properties not shared by pantomimed reaching (Goodale et al., 1994). For example, the time and magnitude of peak velocity, the maximum height of the hand, and the maximum grip aperture, are all significantly different when reaching to imagined than to perceived objects. Reaching and grasping gestures towards imagined objects exhibit the distinctive pattern that is observed when subjects are asked to pantomime a reaching and grasping motion. There is considerable evidence that the visuomotor system is itself encapsulated (Milner & Goodale, 1995) and, like the visual system, is able to respond only to information arriving from the eyes, which often includes visual information that is not available to consciousness. As with the visual system, only certain limited kinds of modulations of its characteristic behavior can be imposed by cognition. When we examine signature properties of the encapsulated visuomotor system, we find that mental images do not engage it the way that visual inputs do. In the next section we provide other reasons to doubt that the early visual system interprets visual images as though they were pictorial displays.

7.4 The search for a real spatial display

Given the emptiness of the “functional space” explanation, there are several possible ways to proceed in trying to explain the apparent spatial quality of images. The first and most obvious, as I have argued in the last chapter, is to recognize that most of the metrical effects (scanning times, time to recognize details in images of different size, and so on) are not due to intrinsic or format properties of images, but to the way observers understand the task and to their psychophysical ability to generate relative time intervals related to the time they believe certain imagined events would take. In other words, the research strategy ought to be, first to determine whether mental simulation, which does not attribute any particular format to images, would explain the pattern of results. But even if we discount the inference to from experiments such as mental scanning to the picture theory, we still need to explain such puzzles as how imagining geometrical diagrams helps us solve problems in geometry. Given the general failure to develop general models of spatial representation without posting Cartesian coordinates (and therefore, the Cartesian plane) it is reasonable that we try to take the bull by the horns and try to find an actual literal spatial medium in the brain. This approach at least has the virtue of making an explicit testable claim, which, despite its initial implausibility, might provide some explanatory advantage over an illusive metaphor or an appeal to the totally illusive “functional space.” Despite the advantage of this approach, until recently, surprisingly few people were willing to endorse the literal assumption that there is a spatial display in the brain. In recent years much of the work directed at supporting the picture-theory of mental imagery has been carried out in neuroscience, and much of that has involved neural imaging. In what follows I will look at this work from several perspectives, beginning with a general methodological discussion of the status of neuroscience evidence in the imagery debate.

7.4.1 Preface: Does biological evidence have a privileged status in this argument?

Before proceeding with a review of some of the relevant neuropsychological findings, I should pause to make one important prefatory point. Many writers impressed with the evidence from neuroscience write as though such evidence renders all previous behavioral evidence obsolete. Nothing could be further from the truth. It was behavior (and phenomenological) considerations that raised the puzzle about mental imagery in the first place and that suggested the picture theory. And it is a careful consideration of that evidence and its alternative interpretations that has cast doubt on the picture theory. Even if we found real colored stereo pictures displayed on the visual cortex, the problems raised thus far in this article would remain and would continue to stand as evidence that the cortical pictures were not serving the function attributed to them. For example, the fact that phenomena such as mental scanning and others are cognitively penetrable is strong evidence that whatever is displayed on the cortex is not what is responsible for the patterns of behavior observed in mental imagery studies. Similarly the question of what is responsible for the facilitation of recall and problem solving that accompanies the phenomenology of mental imagery requires a psychological process theory to link any proposals about the nature of mental images with actual performance data. It is important to understand that the mere fact that the data are biological does not give it a privileged status in deciding the truth of a psychological process theory, especially one whose conceptual foundations are already shaky.

In examining the behavioral evidence so far I have distinguished two distinct types of claims. The first concerns the nature or the format of mental images and the second concerns the nature of the mechanism used in processing them. We saw that although these may be related questions, they are also largely independent, since it is logically possible for the visual system to be involved in both vision and mental imagery and yet in neither case generate or process picture-like representations. Similarly it is possible for representations to be topographically organized and yet have nothing to do with visual perception, nor with any depictive character of the representation. In a certain sense the physical instantiation of any cognitive representation *must* be topographically organized. Fodor and I (Fodor & Pylyshyn, 1988) have argued that any form of representation that is adequate as a basis for cognition must be compositional, in the sense that the content of a complex representation must derive from the content of its parts and the rules by which the complex is put together (the way the meaning of sentences is compositional and depends on the meaning of

its parts together with the way they are syntactically put together). The physical instantiation of any representation that meets the requirement of compositionality will itself exhibit compositionality (Pylyshyn, 1984a, pp54-69; Pylyshyn, 1991b). In the case of symbolic representations, parts of expressions are mapped recursively onto parts of physical states and syntactic relations are mapped onto physical relations. As a result, there is a very real sense in which the criteria in the Kosslyn quotation at the beginning of section 6.4.1 are met by any compositional physical symbol system, not just a depictive one. Note that in a digital computer, representations are compositional and topographically distributed and yet are generally not thought to be depictive, whereas when they are supposed to be depictive, as with encoded images, their topographical distribution generally does not mirror the physical layout of the picture, so the question of the spatial distribution of images, the question of whether they are depictive, and the question of whether they are connected with vision are logically independent questions.

In addition to these considerations, it also true that in the present state of neuroscience, the sorts of evidence being considered is far from being adequate to the task of deciding among competing cognitive theories. The primary source of evidence in cognitive neuroscience continues to be neural imaging. This fairly recent technique in the neurologist's armament, which has turned out to be extremely important in clinical neuroscience, is rather crude when it comes to deciding such questions as whether common mechanisms are used in different psychological processes. The technique relies on assumptions about the relation between blood flow and metabolism, and between metabolism and cognitive processing activities of the brain. Yet it is far from clear what kind of neural activity is indicated by increased blood flow; whether, for example, it indicates activation or inhibition (e.g., the active attempt to suppress otherwise disrupting visual activity); whether it is associated with the same activity that is responsible for the sorts of psychophysical results reported earlier, or activity correlated with the experience of "seeing," or something entirely different. It is even problematic whether increased cerebral flood flow indicates increased information processing activity (Fidelman, 1994; Haier, Siegel, Neuchterlein, Hazlett, Wu, Paek, Browning, & Buchsbaum, 1988). There is also concern that the widely used subtractive technique (in which the activity map associated with a control condition is subtracted from the activity map associated with an experimental condition) has problems of its own (Sergent, 1994), as well as being predicated on the assumption that the function under study is a modular one that involves activity in a particular brain region each time it occurs, regardless of the circumstances (Sarter, Berntson & Cacioppo, 1996). Even processes known to be functionally modular, such as the syntactic aspect of language processing, often give inconsistent neural imaging results (Démonet, Wise & Frackowiak, 1993), so we ought to be wary when drawing conclusions about functions like mental imagery, which the empirical data give us every reason to believe is not modular since most, if not all of its properties are cognitively penetrable (Pylyshyn, 1981). These and other concerns are with us in all the neural imaging studies. While they may eventually be circumvented by better technologies for measuring brain activity and for more precise localization of such activity in time and space, and even more importantly, as we develop a better understanding of the questions that we need to address, they remain serious concerns for the foreseeable future. For the time being we should treat neural imaging evidence the way we treat all other essentially correlational evidence, such as reaction time, error rate, or ERP – as indicators whose validity needs to be independently established, rather than as direct measures of the variables of primary interest.⁶¹

7.4.2 The search for a display in the brain

As we saw earlier, the question of whether mental imagery uses the visual system is intimately tied to the issue of what constitutes the uniquely visual system. If the question is merely about whether some

⁶¹ In a recent paper (Kosslyn, Pascual-Leone, Felican, Camposano, Keenan, Thompson, Ganis, Sukel, & Alpert, 1999a) showed that if area 17 is temporarily impaired using repetitive transcranial magnetic stimulation (rTMS), performance on an imagery task is adversely affected (relative to the condition when they do not receive rTMS), suggesting that the activation of area 17 may be not only correlational, but may also play a causal role. However, this result must be treated as highly provisional since the nature and scope of the disruption produced by the rTMS is not well established and the study in question lacks the appropriate controls for this critical question; in particular, there is no control condition measuring the decrement in performance for similar tasks not involving imagery.

mechanisms used in vision are also used in visual imagery, then the answer is clearly *yes*, though for the uninteresting reason that they both involve accessing memory and making inferences. The involvement of visual mechanisms in mental imagery is of interest to the picture theorists primarily because of the possibility that the particular role played by the early visual system in processing mental images will vindicate a version of the picture theory, by showing that imagery does indeed make use of a special sort of spatial display (this is explicitly the claim in Kosslyn, 1994). The question that naturally arises is whether we can make a case for this view by examining the neurophysiological evidence concerning which areas of the brain are involved in mental imagery and in visual perception. It is to this question that I now turn our attention, beginning with an examination of the evidence cited in support of the claim that mental images are neurally realized in a topographic or spatial display format.

An argument along the following lines has been made in the recent neuroscience literature (Kosslyn et al., 1999a; Kosslyn, Thompson, Kim, & Alpert, 1995). Primary visual cortex (Area 17) is known to be organized retinotopically (at least in monkey brain). So if the retinotopic visual area is activated when subjects generate mental images, it would suggest that (1) the early visual system is involved in some aspect of visual mental imagery, and (2) during imagery the cognitive system provides the visual system with inputs in the form of a topographic display – in other words it generates a display that is laid out in a spatial or “depictive” form (i.e., like a two-dimensional picture). Writers espousing the picture theory routinely cite evidence showing that early vision area of the brain is organized retinotopically. They do this sometimes while vehemently insisting that they do not hold a literal display-view or picture view of mental images, but rather something weaker, such as the “functional space” view discussed earlier. But a “functional space” view (whatever that could possibly mean – perhaps, as I suggested above in section 7.1– it means nothing) is not furthered by evidence such as that of (Tootell, Silverman, Switkes, & de Valois, 1982), showing the pattern of activation of monkey visual cortex by visual stimulation. Tootell et al. trained macaques to stare at the center of a pattern of flashing lights, while the monkeys were injected with radioactively tagged 2-deoxydextroglucose (2-DG), whose absorption is related to metabolic activity. Then the doomed animal was sacrificed and a record of 2-DG absorption in its cortex was developed. This record showed a retinotopic pattern in V1, that corresponded closely to the pattern of lights (except for a cortical magnification distortion). In other words, it showed a *picture* in visual cortex of the pattern that the monkey had received on its retina, written in the ink of metabolic activity, as shown in Figure 7-2. This led some people to conclude that we now know that a picture in primary visual cortex appears during visual perception and is the basis for visual perception. Although no such maps have been found for imagery, there can be no doubt that this is what the picture-theorists believe is there and is responsible for both the imagery experience and the empirical findings reported when mental images are being used.

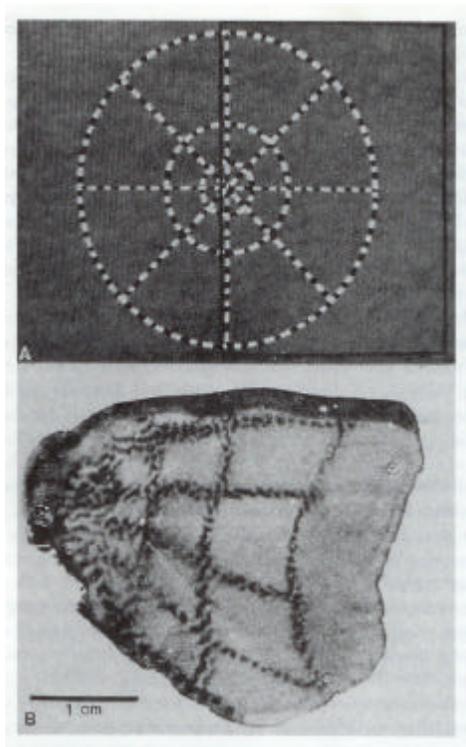


Figure 7-2. The top photograph (A) shows the stimulus used by (Tootell et al., 1982) to demonstrate the retinotopic organization of the visual cortex in the Macaque. The monkey stared at the top pattern, formed by flashing lights, while it was injected with the radioactively tagged tracer 2-DG (deoxydextroglucose). Then the pattern of radioactivity on its primary visual cortex was measured. Figure B shows the pattern of activity actually found.

The idea that in mental imagery, cognition provides input into the early visual system that is then used to “perceive” that input and give it a (possibly new) interpretation is very much in keeping with the views developed earlier from behavioral evidence (section 6.5). It is also in keeping with the subjectively satisfying picture theory of the form of mental images. Given this background and the impotence of the “functional space” idea to provide an explanation of the mental imagery results, it is no surprise that any evidence of the involvement of early vision in mental imagery would be received with a great deal of enthusiasm by those who hold the picture view. It has been tacitly assumed to be the link that will combine the mechanisms of vision and mental imagery while at the same time showing that both involve a literal spatial display in the brain (much like that pictured in Figure 7-2). In section 7.4.3 (especially in (3)) the relevance of the Tootell work to the picture theory of mental imagery will be raised again.

With this as background, we ask first, whether there is evidence for the involvement of early vision in mental imagery. The answer is there is some evidence that mental imagery involves areas of striate cortex associated with vision, though the claim is far from being universally accepted. Most of this evidence has come from studies using neural imaging to monitor regional cerebral blood flow, and also from studies of brain damaged patients. While some neural imaging studies report activity in topographically organized cortical areas (Kosslyn et al., 1999a; Kosslyn et al., 1995), most have reported that only later visual areas, the so-called visual association areas, are active in mental imagery (Charlot, Tzourio, Zilbovicius, Mazoyer, & Denis, 1992; Cocude, Mellet & Denis, 1999; D’Esposito, Detre, Aguirre, Stallcup, Alsop, Tippet, & Farah, 1997; Fletcher, Shallice, Frith, Frackowiak, & Dolan, 1996; Goldenberg, Mullbacher & Nowak, 1995; Howard, ffytche, Barnes, McKeefry, Ha, Woodruff, Bullmore, Simmons, Williams, David, & Brammer, 1998; Mellet, Petit, Mazoyer, Denis, & Tzourio, 1998; Mellet, Tzourio, Crivello, Joliot, Denis, & Mazoyer, 1996; Roland & Gulyas, 1994b; Roland & Gulyas, 1995; Silbersweig & Stern, 1998); but see the review in (Farah, 1995) and the some of the published debate on this topic (Farah, 1994; Roland & Gulyas,

1994a, 1994b). There is some reason to think that the activity associated with mental imagery occurs at many loci, including higher-levels of the visual stream (Mellet et al., 1998).

Problems comparable to those faced by neural imaging studies arise with the use of clinical populations (Trojano & Grossi, 1994). It is hard enough to find “pure” cases in which the lesions are highly localized and their locations accurately known, but when such patients are found, the evidence even less clearly supports the involvement of the earliest (topographically organized) areas of visual cortex (Roland & Gulyas, 1994b). If the specifically visual areas of the brain are responsible for mental imagery then it follows that damage to those areas should impair both vision and imagery functions. Yet there is considerable evidence for the dissociation between the capacity for visual imagery and such visual deficits as cortical blindness (Chatterjee & Southwood, 1995; Dalman, Verhagen & Huygen, 1997; Goldenberg et al., 1995; Shuren, Brott, Schefft, & Houston, 1996), dyschromatopsia (Bartolomeo, Bachoud-levi & Denes, 1997; De Vreese, 1991; Howard et al., 1998), visual agnosia (Behrmann, Moscovitch & Winocur, 1994; Behrmann, Winocur & Moscovitch, 1992; Jankowiak, Kinsbourne, Shalev, & Bachman, 1992; Servos & Goodale, 1995) and visual neglect (Beschin, Cocchini, Della Sala, & Logie, 1997). The independence of imagery (as measured by performance on the usual mental imagery tasks, such as mental scanning) and vision is also supported by a wide range of both brain-damage and neuroimaging data and the dissociation has been shown in both directions. The case for independence is made all the stronger by the widespread evidence that blind people show virtually all the skills and psychophysical phenomena associated with mental imagery. They may even report a comparable phenomenology concerning object shape as that of sighted people. It has also been suggested that what characterizes patients who show a deficit on certain specific imagery-generation tasks (e.g., imagining the color of an object) is that they lack the relevant knowledge of the appearance of objects (Goldenberg, 1992; Goldenberg & Artner, 1991). On the other hand, insofar as blind people know (in a factual way) what objects are like (including aspects of their “appearance” – such as their shape, size, orientation, as well as some of their features that show up clearly in vision, such as smoothness) it is not surprising that they should exhibit some of the same psychophysical behaviors in relation to these properties.

In order to support the “cortical display” version of the picture theory it is important not only that the visual system be involved in imagery, but also that the areas involved are the topographically mapped areas of cortex and that their involvement be of the right kind. In particular it is important that the topographic mapping reflect the spatial properties of the phenomenal image. Very few neuroscience studies meet this criterion, even when they do show that the visual areas are activated during mental imagery. One of the few examples of a finding that has been assumed to meet this criterion was reported in (Kosslyn et al., 1995) insofar as this research relates a specifically spatial property of mental images (their size) to a pattern of neural activity. It showed that “smaller” mental images (mental images that the observer subjectively experiences as occupying a smaller portion of the available “mental display”) are associated with more activity in the posterior part of the medial occipital region while “larger” images are associated with more activity in the anterior parts of the region. Since this pattern is similar to the pattern of activation produced by small and large retinal images, respectively, it has been taken to support the claim that the activation of visual cortical areas during mental imagery corresponds to the activation of a cortical display which maps represented space onto cortical space. It is for this reason that (Kosslyn et al., 1995, p 496) feel entitled to conclude that the findings “indicate that visual mental imagery involves ‘depictive’ representations, not solely language-like descriptions.” But notice that even if the cortical activity monitored by PET scans in this study corresponds to a mental image, the evidence only shows that a larger mental image involves activity that is located where parts of larger retinal images tend to project. The reason that larger retinal images activate the regions that they do in the case of vision is related to the way that the visual pathway projects from the periphery of the retina to the occipital cortex, not because this pattern of activation maps the size of the image onto a metrical spatial property of its cortical representation (Fox, Mintun, Raichle, Miezin, Allman, & Van Essen, 1986). In particular it is significant that the data do not show that image size is mapped onto the size of the active cortical region, as would be required by the cortical display view, and as would be required if images had the property that they “preserve metrical information” as claimed by Kosslyn and others, or as required in order to account for the imagery data reviewed earlier. For example,

the explanation for why it takes less time to notice features in a large image is supposed to be that it is easier for the mind's eye to see a large cortical display, not that the image is located in the more anterior part of the medial occipital cortex. The property of being located in one part of the visual cortex rather than another simply does not bear on any of the evidence regarding the spatial nature of mental images discussed earlier. Consequently the finding cannot be interpreted as supporting the picture theory of mental imagery, nor does it in any way help to make the case for the cortical display or literal-space view. Those of us who eschew dualism are perfectly prepared to accept that *something* different happens in the brain when a different phenomenal experience occurs, consequently something different must occur in the brain when a larger image is experienced. The point has never been to dispute materialism, but only to question the claim that the content of an image maps onto the brain in a way that helps explain the imagery results (e.g., mental scanning times, image-size effects on information access, etc) and perhaps even the subjective content of mental images. A literally larger brain image corresponding to a larger phenomenal image might have done that, since it might at least have suggested a possible account for such findings as that it takes longer to scan larger image distances and why it takes longer to see details in smaller images, but a merely different locus of brain activity is no help in this regard.

7.4.2.1 *The argument from clinical cases of brain damage*

A different kind of evidence for the neural display view of mental imagery was reported by (Farah, Soso & Dasheiff, 1992) based on a clinical case. Farah reported that a patient who developed tunnel vision after unilateral occipital lobectomy also developed tunnel imagery. If the cortical display were involved in both vision and imagery, and if the peripheral parts of the display were damaged, then it would explain the parallel deficits. This case suggests that tunnel vision and tunnel imagery may have a common underlying neural basis, and that this basis may be connected with the visual system (at least in the broad sense), but it does not show that this basis has anything to do with a topographical mapping of the spatial property of images onto spatial properties of a neural display. In fact in this case there is an explanation for the Farah et al. finding that does not even imply the involvement of visual mechanism, let alone a cortical screen. If you believe, as I do, that such subjective phenomena as having large or small images and having tunnel imagery generally arise from the implicit task requirement of simulating various aspects of what things would look like to you, then it is important that in the (Farah et al., 1992) study the patient had nearly a year of post-surgery recovery time before the imagery testing took place. During this time she would have become familiar with what things *look like* to her now, and was therefore in a position to simulate her visual experience by producing the relevant phenomena when asked to image certain things (e.g., to answer appropriately when asked at what distance an image of a horse would overflow her image). As I have often pointed out, this would not be a case of the patient being disingenuous or being influenced by the experimenter, which Farah et al. were at pains to deny, but of doing her best to carry out the task required of her, namely to "imagine how it would look."⁶²

The phenomenon of *visual or hemispacial neglect* has also often been cited in support of the display theory. In a famous paper (Bisiach & Luzzatti, 1978) reported two patients who had the classical syndrome called visual neglect, in which they tend not to report details on one side of a scene (in this case the left side). Bisiach & Luzzatti found that both patients also tended not to report details from the left side of their mental images. More interestingly, they would report the details that appeared to be missing in the left side of their image if they were asked to turn around and report their image of the scene viewed from the opposite perspective. This is indeed an interesting phenomenon and is frequently cited in favor of a cortical-screen view as opposed to a symbolic view of the form of representation underlying imagery (after all, it's hard to think why a symbolic representation would favor one side of a scene over another). The explanation in terms of a cortical display is straightforward: if one side of the display is damaged then one would expect that to affect the same side of both visual perception and visual imagery. But it has since

⁶² A possible control for this explanation would be to study patients whose loss of peripheral vision and delay in testing followed roughly the same pattern as Farah's patient but in which the damage was purely retinal. The expectation is that under the same instructional conditions such patients would also exhibit tunnel imagery, even though there was presumably no relevant cortical damage involved.

turned out that visual neglect and imaginal neglect are completely dissociable. There are patients who neglect one side of a visual scene but do not neglect one side of their image, patients who neglect one side of their image but do not neglect one side of their visual perception, and even patients who neglect one side of their visual perception and neglect the other side of their image. In any case, the idea that what is damaged in visual neglect is one side of a display seems too simplistic⁶³; it does not account for the dissociation between visual and imaginal neglect (Coslett, 1997), for the amodal nature of neglect (the deficit shows up in audition as well as vision, Marshall, 2001; Pavani, Ladavas & Driver, 2002), for the fact that “neglected” stimuli typically provide some implicit information (Driver & Vuilleumier, 2001; McGlinchey-Berroth, Milberg, Verfaellie, & Grande, 1996; Schweinberger & Stief, 2001), for the characteristic response bias factors in neglect (Bisiach, Ricci, Lualdi, & Colombo, 1998; Vuilleumier & Rafal, 1999) and for the fact that higher-level strategic factors appear to play a central role in the neglect syndrome (Behrmann & Tipper, 1999b; Bisiach et al., 1998; Landis, 2000; Rode, Rossetti & Biosson, 2001). The “damaged display” view also does not account for the large number of cases of object-centred neglect (Behrmann & Tipper, 1999a; Tipper & Behrmann, 1996). Moreover, as (Bartolomeo & Chokron, 2002) have documented (and reiterate in their commentary), the primary deficit in neglect is best viewed as the failure of stimuli on the neglect side to attract attention.

I agree with **Bartolomeo & Chokron** as well as with **Burgess** and with **Chatterjee**, that it would be odd for a symbolic encoding system by itself to have directional preferences, such as found in neglect, and I also agree that most cases of imaginal neglect are unlikely to be due to tacit knowledge. Having granted that, one must then ask why we should expect the explanation for such directional properties to be found in the format of representations or in the medium of the Tootell Display. Deficits such as neglect, whether in vision or in imagery, represent a failure to orient to one side or the other, and the direction may have more to do with direction in the world, than direction in an image. As in the case of the **Gosselin & Schyns** example discussed earlier, orienting is a world-directed response. There is considerable merit in **Bartolomeo & Chokron’s** suggestion that perhaps “visual imagery involves some of the attentional-exploratory mechanisms that are employed in visual behavior ... [so] the ‘perceptual’ aspects of visual mental images might thus result not from the construction of putative ‘quasi-perceptual’ representations, but from the engagement of attentional and intentional aspects of perception in imaginal activity.” In other words when attending to the left side of an image, patients are actually *orienting towards* the left side of the perceived world (or perhaps of their body). Even with eyes closed we have accurate recall, at least for a short time, of the location of things in the world immediately around us (see the remarks about this by **Ingle**) and it may be in relation to these world-locations that attention orients. As I speculated in section 5.3 of the target article, it may be generally the case that it is the physical space outside the head that gives imagery its putative spatial character and that it does so by virtue of how mental contents are associated with (or bound to) places in the perceived world. Although the case is clearest when the spatial layout is visually perceived while imagining, and aspects of what is imagined are associated with places in the perceived layout through visual indexes, there is no reason why this should not also hold when real space is sensed through other modalities, such as proprioceptive or kinesthetic modalities (indeed motor-space analogs of visual indexes, called Anchors, were proposed when the visual index theory was first introduced in Pylyshyn, 1989). It is known that people are very good at orienting to stimuli that are not visually present (Attneave & Farrar, 1977). The ability to bind objects of thought to the location of perceived (or recalled) external objects allows us to orient to them, thereby enhancing the illusion that things are laid out inside the head the way that the corresponding things are laid out outside the head, thus reinforcing the intentional fallacy.

⁶³ (Kosslyn, 1994) does not explicitly claim that the “depictive display” is damaged in cases of neglect, preferring instead to speak of the parallels between the vision and imagery systems. But to be consistent he *should* claim that the display is damaged, since the point of the display is that it allows one to explain spatial properties of imagery by appealing to spatial properties of the display. Simply saying that it shows that vision and imagery use the same mechanisms does not confer any advantage to the depictive theory, since *any* theoretical imagery format can claim that (including the null hypothesis, which is why it is there; to provide a test for the irrelevance of assumptions about the image format).

7.4.3 What would it mean if all the neurophysiological claims turned out to be true?

Results such as those of Kosslyn et al. and Farah et al. have been widely interpreted as showing that retinotopic picture-like displays are generated on the surface of the visual cortex during imagery and that it is *by means of this spatial display* that images are processed, patterns perceived from mental images and the results of mental imagery experiments produced. In other words these results have been taken to support the view that mental images *are literally two-dimensional displays* projected onto primary visual cortex. I have already suggested some reasons why the neurophysiological evidence does not warrant such a strong conclusion (and that a weaker “functional space” conclusion is too weak to support the claims of a special form of representation for mental images). In addition, it should be remembered that standing against this interpretation of the neurophysiological findings, is an enormous amount of behavioral evidence that cannot be ignored. If we are to take seriously the conclusions suggested by the researchers who use neuroscience evidence to argue for the picture-theory (or the cortical-display theory), we need to understand the functional role that could be played by a literal picture being projected onto visual cortex. In particular we need to ask ourselves the following question. Suppose that (contrary to fact) it is one day discovered that when people entertain a visual image there really is a picture displayed on the visual cortex and the picture has all the spatial and depictive properties claimed for it (say, in the quotation reproduced in section 6.4.1). What would be the empirical implications of such a conclusion, and is the evidence regarding the function of imagery in mental activity consistent with such implications? And, perhaps even more interestingly, what would we need to assume about the cognitive system (i.e., about the function carried out by the “mind’s eye”) for this sort of theory to work?

Here is a short summary of some behavioral findings that raise questions about the validity of a story that assumes that a picture is projected onto the visual cortex. It would be hard to justify the leap from the sorts of neuropsychological data we have considered to a picture theory of mental imagery unless the following sorts of evidence could be addressed, at least in outline.

1. There is a great deal of evidence now that the capacity for visual imagery is independent of the capacity for visual perception. If the early visual areas are the site of mental images and it is their topographical form that is responsible for the visual image results discussed earlier, it is hard to see why congenitally blind people produce the same imagery results (such as scanning times) as sighted people (Carpenter & Eisenberg, 1978; Zimler & Keenan, 1983). Cortically blind patients can also report imagery while some people who fail to report imagery have normal sight (Chatterjee & Southwood, 1995; Dalman et al., 1997; Goldenberg et al., 1995). Similarly, cerebral achromatopsia can be dissociated from the capacity to have colorful images (Bartolomeo et al., 1997; Shuren et al., 1996), hemispatial neglect can be manifested independently in vision and imagery (Beschlin et al., 1997; Coslett, 1997; Guariglia, Padovani, Pantano, & Pizzamiglio, 1993) and visual agnosia can occur with intact mental imagery ability (Behrmann et al., 1994; Behrmann et al., 1992; Servos & Goodale, 1995). While there have been attempts to explain these dissociations by attributing some of the lack of overlap to an “image generation” phase that is presumably involved only in imagery (see the recent review in, Behrmann, 2000), this image-generation proposal does account for much of the evidence for the independence of imagery and vision, in particular it cannot explain how one can have spared imagery in the presence of such visual impairments as total cortical blindness (op.cit.).
2. The conclusion that many people have drawn from the neural imaging evidence cited earlier, as well as from the retinotopic nature of the areas that are activated, is that images are two-dimensional retinotopic displays. But that can’t be literally the case. The psychophysical evidence shows that mental images are, if anything, three-dimensional inasmuch as the phenomenology is that of seeing a three-dimensional scene. Moreover, similar mental scanning results are obtained in depth as in 2D (Pinker, 1980) and the phenomenon of “mental rotation” – one of the most popular demonstrations of visual imagery – is indifferent as to whether rotation occurs in the plane of the display or in depth (Shepard & Metzler, 1971). Neither can the retinotopic “display” in visual cortex literally be three-dimensional. The spatial properties of the perceived world are not reflected in a volumetric topographical organization in the brain: as one penetrates deeper into the columnar structure of the cortical surface one does not find a

representation of the third dimension of the scene. Furthermore, images represent other properties besides the spatial ones. For example, they represent color and luminance and motion. Are these also to be found displayed on the surface of the visual cortex? If not, how do we reconcile the apparently direct spatial mapping of 2D spatial properties with a completely different form of mapping for depth and for other contents of images of which we are equally vividly aware?

3. The cortical display view of imagery assumes that mental images consist not only in the activation of a pattern that is the same as the pattern activated by the corresponding visual percept, but it also assumes that such a pattern mimics the retinotopic projection of a corresponding visual scene. If such an activation pattern is to correspond to our mental image then one would have to assume that the pattern displayed in the cortex is an extension of the retinal projection and incorporates a larger region of the scene than that covered by the retina. Otherwise the pattern would not correspond to what we “see” in our mind’s eye. Among the arguments put forward for the existence of an inner display is that it is needed to explain stability of the percept over eye movements and the invariance of recognition with translations of the retinal image (Kosslyn, 1994, Chapter 4). It has also been suggested that the display is needed to account for the completion of the apparently detailed visual percept in the face of highly incomplete and partial sensory data (Kosslyn & Sussman, 1995). The assumption behind these arguments is that incomplete sensory data are augmented in a visual display before being given over to the visual system responsible for recognition (and that presumably leads to our conscious awareness). While it may well be that neural processes are responsible for certain cases of “filling in” phenomena, it is also clear that they do not do so by completing a filled display when only a partial one is presented by vision (for a sophisticated discussion of the issue of filling-in, which makes it clear that cases of neural completion do not imply “analytical isomorphism,” see Pessoa et al., 1998).

Notwithstanding the fact that the early part of the visual cortex appears to be organized retinotopically, it is highly unlikely that this retinotopic organization serves to shield the inner eye from the incompleteness and instability of the incoming sensory data and thereby gives rise to such properties as the invariance of recognition over different retinal locations. There is every reason to believe that vision does not achieve stability and completeness, despite rapidly changing and highly partial information from the sensors, by accumulating the information in a spatially extended inner display. In fact the subjective experience that we are examining an inner display in vision is an illusion.⁶⁴ Even if we had such a display we would not see it, we see the world and it is the world we see that appears to us in a certain way. The data are unequivocal about this. The evidence shows that the assumption that visual stability and saccadic integration is mediated by an inner-display is untenable (Blackmore, Brelstaff, Nelson, & Troscianko, 1995; Irwin, 1991; McConkie & Currie, 1996; O’Regan, 1992) since information from successive fixations cannot be superimposed in a central image as required by this view. Recent evidence also shows that there is no central repository where visual information is enriched and accumulated to form a detailed panoramic view of a scene, of the sort we typically experience. Recent work on change blindness shows that the visual system encodes very little information about a scene between fixations, unless attention has been drawn to it (Rensink, 2000; Rensink et al., 1997; Simons, 1996), so there is no detailed pictorial display of any kind in vision, let alone a panoramic one.

4. Although we can reach for imagined objects there are significant differences between the way that the motor system interacts with vision compared with the way it interacts with mental imagery (Goodale et al., 1994), as we saw in section 7.2. Such differences provide strong reasons to doubt that imagery provides input into the dorsal stream of the early vision system where the visuomotor control process begins.

⁶⁴ I agree with (Pessoa et al., 1998) that use of the term “illusion” here is perhaps unfortunate since it suggests that what we *should* experience – the *correct* percept – would be what is mapped isomorphically on the visual cortex, which is the very assumption we are questioning. I intend merely to emphasize that our intuitive idea of what we are examining is wrong and in that sense illusory.

5. Accessing information from a mental image is very different from accessing information from a scene. To take just one simple example, we can move our gaze as well as make covert attention movements relatively freely about a scene, but not on a mental image. Try writing down a 3 x 3 matrix of random letters and read them in various orders. Now imagine the matrix and try doing the same with it. Or, for that matter, try spelling a familiar word backwards by imagining it written. Unlike the 2D matrix, some orders (e.g., the diagonal from the bottom left to the top right cell) are extremely difficult to scan on the image. If one scans one's image the way it is alleged one does in the mental scanning experiments, there is no reason why one should not be able to scan the matrix freely. Of course one can always account for these phenomena by positing various properties specific to the images generated by cognitive processes, such as assuming a limit on the number of elements that can be drawn, or assuming that elements decay. Such assumptions are completely ad hoc. For example, visual information does not appear to fade as fast and in the same way as has to be assumed in these accounts of the decay from cognitively generated images (Ishai & Sagi, 1995) nor does it appear to fade in the case of images used to investigate mental scanning phenomena (which, like the map used by Kosslyn et al., 1978, are much more complex). Moreover the hypothesized fading rates of different parts of an image have to be tuned post hoc to account for the fact that it is the *conceptual* as opposed to the *graphical* complexity of the image determines how the image can be read and manipulated (i.e., to account for the fact that what one sees the image *as*, how one interprets it, rather than its geometry, is what determines its apparent fading). For example, it is the conceptual complexity of images that matters in determining the difficulty of an image superposition task (Palmer, 1977), or to how quickly figures can be "mentally rotated" (Pylyshyn, 1979b).
6. The centrality of conceptual properties of an image is an extremely general property. It applies to the question of how images are distorted or transformed over time, to how mental images can or can't be (re)interpreted, and to how they can fail to be determinate in ways that no picture can fail to be determinate (Pylyshyn, 1973, 1978, 1984a). For example, no picture can fail to have a size or shape or can fail to indicate which of two adjacent items is to the left and which to the right, or can fail to have exactly n objects (for some n), whereas mental images can be indeterminate in many ways. Not surprisingly, there are many ways of patching up a display to accommodate any such findings. For example one can add assumptions about how images are tagged as having certain properties (perhaps including the property of not being based on real perception) and how they have to be incrementally refreshed from non-image information stored in memory, etc., thus providing a way to bring in conceptual complexity and indeterminacy through the image generation function. With each of these accommodations, however, one gives the actual image less and less of an explanatory role until eventually one reaches the point where the display becomes a mere shadow of the mechanism that does its work elsewhere, as when the behavior of an animated computer display is determined by an extrinsic encoding of the principles that govern the animation rather than by intrinsic properties of the display itself.
7. The visual appearance of information projected onto a retinotopic display is very different from the appearance of information in a mental image. Images on the retina, and presumably on the visual cortex, are subject to Emmert's law: Retinotopic images superimposed onto a visual scene change their apparent size depending on the distance of the background against which they are viewed. Mental images imagined over a perceived scene do not change their size as the background recedes, providing strong evidence that they are not actually projected onto the retinotopic layers of the cortex.
8. Images do not have the signature properties of early vision (such as the properties discussed in Hochberg, 1968). If we create mental images from descriptions we do not find such phenomena as spontaneous interpretation of certain 2D shapes as representing 3D objects, spontaneous reversals of bistable figures, amodal completion or subjective contours (Slezak, 1995), visual illusions, as well as the incremental construction of visual interpretations and reinterpretations over time, as different aspects are noticed.

It appears that if having a mental image consists of certain activity in the visual cortex, this is not activity that can be described as a topographical display of the image in the sense in which retinal stimulation is such a display. In particular, the activity is not something that must be visually interpreted, the way that retinal activity must be interpreted by the early vision system. As to whether the activity is in some other way similar to the activity involved in visual perception, this remains an open empirical question. The critical assumption that is being questioned is not that entertaining mental images has some connection with visual perception, it is the assumption that entertaining an image consists in visually interpreting some special form of representation, in particular a form of representation that is picture-like or, as some people have been calling it “depictive.” Although the term depictive is not well defined beyond its metaphorical connection to pictures, it is intended to suggest that the form is pre-perceptual or preconceptual, and therefore in need of interpretation by the usual early visual processes. This is why people have been concerned to show that activity associated with mental imagery occurs in areas of the cortex known to be retinotopically mapped. But, as I argued earlier, just because there is activity in an area that is retinotopically mapped is not sufficient reason to conclude either that the mental images themselves are retinotopically mapped in a way that preserves spatial properties, or that if they are, they serve as input to a visual system that perceives them in a way determined by their retinotopic shape. And these, rather than the mere involvement of parts of the visual system, is what has been central in the mental imagery debate, at least since (Pylyshyn, 1973).

7.4.4 Mental Imagery and the visual system: Is the ‘mind’s eye’ just like a real eye?

Here is another way to think about the question of whether mental images could plausibly consist of displays projected on the cortex. Suppose that, contrary to fact, one day it is discovered that when we entertain a mental image there is an actual projection of that very image on the surface of primary visual cortex (or, for that matter, on the retina itself; the conceptual issue would be the same in either case). What would that tell us about the nature and role of mental images in cognition? We have known at least since Descartes that there is an image on our retinas when we perceive, and perhaps there is also some transformed version of this image on our cortex, yet knowing this has not made us any wiser about how vision works. Indeed, ruminating on the existence of an image just raised such problems as why we do not see the world as upside down, given that the image on the retinas is upside down. The temptation to concretize a literal “mind’s eye” may be very strong but it leads us at every turn into blind alleys.

Some of the psychophysical evidence that is cited in support of a picture view of mental imagery suggests a similarity between the mind’s eye and the real eye that is so remarkable that it ought to be an embarrassment to picture-theories. It not only suggests that the visual system is involved in imagery and that it examines a pictorial display, but it appears to attribute to the “mind’s eye” many of the properties of our own eyes! For example, it seems that the mind’s eye has a visual angle like that of a real eye (Kosslyn, 1978) and that it has a field of resolution which is also the same as our eyes; it drops off with eccentricity according to the same function and inscribes the same elliptical acuity profile as that of our eye (Finke & Kosslyn, 1980; Finke & Kurtzman, 1981a). It even appears that the “mind’s eye” exhibits the “oblique effect” wherein the discriminability of closely-spaced horizontal and vertical lines is superior to that of oblique lines (Kosslyn, Sukel & Bly, 1999b). Since in the case of the eye, such properties arise from the structure of our retinas, it would appear to suggest that the mind’s eye is similarly constructed. Does the mind’s eye then have the same color profile as that of our eyes – and perhaps a blind spot as well? Does it exhibit after-images? And would you be surprised if experiments showed that they did? Of course, the observed parallels could be just coincidence, or it could be that the distribution of neurons and connections in the visual cortex has come to reflect the type of information it receives from the eye. But it is also possible that such phenomena reflect what people have implicitly come to *know* about how things appear to them, a knowledge which the experiments invite them to use in simulating what would happen in a visual situation that parallels the imagined one. Such a possibility is made all the more plausible in view of the fact that the instructions in these imagery experiments explicitly ask observers to “imagine” a certain visual situation – i.e. to imagine that they are in a certain visual circumstances and to imagine what it would look like to see things, say, in their peripheral vision. (I have often wondered whether people who wear thick framed glasses would have a smaller field of vision in their mind’s eye).

The picture that we are being presented, of a mind's eye gazing upon a display projected onto the visual cortex, is one that should arouse our suspicion. It comes uncomfortably close to the idea that properties of the external world, as well as of the process of vision (including the resolution pattern of the retina and the necessity of moving one's eyes around the display to foveate features of interest), are internalized in the imagery system. If such properties were built in to the architecture, our imagery would not be as plastic and cognitively penetrable as it is. If the "mind's eye" really had to move around in its socket (if such a notion is even coherent) we would not be able to jump from place to place in extracting information from our image the way we can. And if images really were pictures on the cortex, the necessity of a homunculus to interpret them would not have been discharged, notwithstanding claims that the entire system had been implemented on a computer (which it has not, except for some trivial sorts of patterns). Computer implementation does not guarantee that what is said about the system, viewed as a model of the mind/brain, is true. As (Slezak, 1995) has pointed out, labels on boxes in a software flowchart (such as "attention" and "display") constitute empirical claims that must be independently justified.

7.4.5 What has the neuroscience evidence done for the "imagery debate"?

Where, then, does the "imagery debate" stand at present? As I suggested near the beginning of this essay, it all depends on what you think the debate was about. If it was supposed to be about whether reasoning using mental imagery is somehow different from reasoning without it, who can doubt that it is? If it was about whether in some sense imagery involves the visual system, the answer there too must be *yes*, since imagery involves similar experiences to those produced by (and, as far as we know, only by) activity in some part of the visual system (though not in V1, according to Crick & Koch, 1995). The big questions are, of course; *in what way* is the visual system involved? Answering that is likely to require a better psychological theory of the decomposition of the visual system itself (as I have tried to provisionally provide in Pylyshyn, 1999) and better alternative proposals for how non-deductive reasoning might proceed. It is much too early and much too simplistic to claim that the way the vision system is deployed in visual imagery is by allowing us to *look at* a reconstructed retinotopic input of the sort that comes from the eye (or at least to some topographically-faithful remapping of this input).

Is the debate, as (Kosslyn, 1994) claims, about whether images are depictive as opposed to descriptive? That all depends on what you mean by "depictive." Is any representation of geometrical, spatial, metrical or visual properties depictive? If that makes it depictive then any description of how something looks is thereby depictive. Does being depictive require that the representation be organized spatially? As I suggested, that depends on what restrictions are placed on "being organized spatially." Does being depictive require that images "preserve metrical spatial information" as has been claimed (Kosslyn et al., 1978)? Again that depends on what it means to "preserve" metrical space. If it means that the image must *represent* metrical spatial information, then any form of representation will have to do that to the extent that it can be shown that people do encode and recall them. But any system of numerals, as well any analogue medium, can represent magnitudes in a useful way. If the claim that images preserve metrical spatial information means that an image *uses spatial magnitudes to represent spatial magnitudes*, then this is a form of the literal picture theory which I have argued is not supported by the evidence. Moreover, a literal picture requires not only a visual system, but a literal mind's eye because the input is a layout of visually uninterpreted features.

The neuropsychological evidence I have looked at, while interesting in its own right, does not appear capable of resolving the issue about the nature of mental images, largely because the questions have not been formulated appropriately and the options are not well understood. One major problem is that we are attempting to account not only for certain behavioral and neurophysiological facts, but we are attempting to do so in a way that remains faithful to certain intuitions and subjective experiences. It is not obvious that all these constraints can be satisfied simultaneously. There is no a priori reason why an adequate theory of mental imagery will map on to conscious experience in any direct and satisfactory way. Indeed if the experience in other sciences and in other parts of cognitive science is any indication, the eventual theory will not do justice to the content of our subjective experience and we will simply have to live with that fact the

way physics has had to live with the fact that the mystery of action-at-a-distance does not have a reductive explanation.

And finally, to end this discussion of the contribution of neuroscience to the imagery debate, I have to add the following anticipatory remarks. The typical response to arguments such as those raised in this section is that it takes the picture theory too literally and nobody really believes that there are actual pictures in the brain. Almost every article I have seen by advocates of the picture theory are at pains to point out that images are not in every way like pictures. For example, (Kosslyn, 1994, p329) states that “images contain ‘previously digested’ information” and (Denis & Kosslyn, 1999) state that “No claim was made that visual images themselves have spatial extent, or that they occupy metrically defined portions of the brain.” But then how do they explain the increase time to scan greater image distances or to report details in smaller images? The explanations of these phenomena *require a literal sense of ‘spatial extent’* otherwise they do not distinguish the depictive story from what I have called the null hypothesis (see the discussion of the ‘functional space’ alternative in section 7.1). And how, if one disclaims the literal view of a cortical display, is one supposed to interpret the concern about whether imagery activates the topographical areas of the visual cortex, or the claim that such activation establishes that images, unlike other forms of representation, are “depictive”? The problem is that while the literal picture-theory or cortical display theory are what provide the explanatory force and the intuitive appeal, it is always the picture *metaphor* that people retreat to in the face of the implausibility of the literal version of the story. This is the strategy of claiming a decisive advantage for the depictive theory because it has the properties cited in the quotation in section 6.4.1, is located in the topographically organized areas of visual cortex, “preserves metrical information” and so on and then, in the face of its implausibility, systematically retreating from the part of the claim that is doing the work – its literal spatial layout. As Bertrand Russell (Russell, 1918/1985, p 71) once said about the advantage of postulating what you would like to prove, the strategy “...has many advantages; they are the same as the advantages of theft over honest toil.”

7.5 What, if anything, is special about mental imagery?

Notwithstanding the skepticism displayed in this book concerning many contemporary views of vision and mental imagery, I believe that visual science has made considerable progress in the past few decades. The trap we have had trouble avoiding is that of taking our introspections at face value, as showing us what vision is like and what its products are. Whatever representations are generated by vision may well be the same, or at least very similar to, those generated when we are engaged in visual imagining. And those representations may well be different from those generated when we reason about more abstract ideas. What we still do not have is an adequate theory of the way in which these sensory-based representations are different from ones that are not accompanied by sensory sensations (though we have had numerous inadequate theories). It may be worth speculating on ways in which these may be different. But first let me review and try to be as explicit as I can about what it is that I am and am not claiming about mental images.

7.5.1 What I am *not* claiming: Some misconceptions about what is being objected to

There has been a great deal of misunderstanding of the position that I have taken in the past on the nature of thought and of mental imagery (e.g., Pylyshyn, 1973, 1981, 1984b). For example, here are a few of the claims that people have attempted to foist on those of us who have been critical of the phenomenologically-inspired “picture” theories of vision, and more particularly of mental imagery.

1) *Mental images don't really exist; or, they are merely “epiphenomenal.”* Prior to the development of an adequate theory of reasoning using mental imagery, the term “mental image” is only the name for the experience of “seeing” without the presence of the object being seen. Nobody can deny the existence of such an experience. Moreover, the content of the experience is a piece of data that we rely on, along with a great many other sources of evidence, in formulating a theory of the what goes on during certain kinds of episodes of information processing. Such episodes are typically, though not necessarily, accompanied by the experience of “seeing” in one’s “mind’s eye” (see the discussion in the previous two chapters). In any case

the claim that mental images are epiphenomenal is at the very least ambiguous: It corresponds either to the claim that we are deluded about what we experience, which is at the very least problematic, or to the claim that a scientific theory of mental imagery will not incorporate things that are like what we experience when we have a mental image, which is almost certainly true. Our experience is not the experience of seeing a mental event, but rather the experience of seeing a possible perceptual world. Consequently no theory of information processing will mirror our phenomenal experience by hypothesizing the existence of objects inside the brain that are the same as the objects of our experience. Nor will a neurological theory do so. That's because the objects of our experience are things in the world (perhaps nonexistent things, but nonetheless things whose proper place is in a world outside the head). As Block has correctly pointed out (Block, 1981), the appeal to epiphenomenalism is either just another way of stating the disagreement about the nature of mental images or else it simply confuses the functional or theoretical construct "mental image" with the experience of having a mental image.

2) *Representations arising from vision are fundamentally different from those involved in mental imagery.* It seems pretty clear – if for no other reason that the fact that both vision and visual imagery involve similar experiences – that there is much in common between these two kinds of representations. What is not so clear is (a) that either of them involve a pictorial display, and (b) whether they have any more in common than the fact that they are both about sensory properties – in other words that they have similar contents or similar subject matters. They may be similar in other respects as well, but here we seem to be at an impasse; neither the evidence nor the state of theorizing has been able to clarify the nature of their similarities. As to their differences, we saw in Chapter 5 that visual perception is able to refer to individual objects in the world being perceived; it is able to make demonstrative reference by selecting or picking out particular individuals without regard to the visible properties of the individuals or to whether any of their properties have been recognized or encoded. Of course when imagery is overlaid on vision (by projecting one's image onto a perceived world) it becomes possible to refer to individuals in the image indirectly by referring to the elements in the world over which they are projected (as we saw in Chapter 7), thus giving one an indirect way of locating imagined individuals in a real space. Whether one can pick out individuals without the benefit of a perceived world is not known. It is not known whether it is possible to pick out several individuals in an image (in the dark or with eyes closed) and carry out such operations as scanning attention from one to another. Such operations appear problematic when applied to a purely mental image. Indeed, it is even problematic to project an image onto a featureless environment such as a *ganzelfeld* (e.g., inside a homogeneous sphere, see Avant, 1965).

3) *The form of the representations underlying mental images is propositional.* It is certainly possible (and even quite plausible) that the content of images can be adequately encoded in a propositional⁶⁵ (or more precisely, quasi-sentential or quasi-logical, or symbolic) form of representation of some sort. Indeed, such an encoding would help explain the conceptual properties exhibit not only by mental images, but also by perception itself (as I suggested, for example, in Pylyshyn, 1973, as well as in Chapter 1). But until someone produces a detailed theory that accounts for some significant imagery phenomena using a propositional encoding, this proposal remains just a suggestion about a plausible form such a theory might take. In the meantime, however, an important use of the idea that images are encoded in propositional form is as a *null hypothesis* against which to test various proposals for image representations. There is something special about such propositional representations. Thanks to the work in formal logic and computation theory over the last half-century we know some important things about what have been called formal languages that we don't know about other forms of representation. Such symbolic representations have a well-defined combinatorial syntax, together with a semantic theory and a proof theory and, if not a full-blooded theory of other types of inference (e.g., inductive, abductive, heuristic), then at least some indication of how semantic properties might be preserved over certain syntactic transformations. In other words, we know some of the essential formal properties of logic-like calculi, as ways of encoding

⁶⁵ I am using the term "propositional" in its common, though somewhat informal sense to mean any language-like symbolic encoding for which a syntax and rules of inference are available. In other words, by "proposition" I really mean a statement in a logical calculus of some sort, such as the predicate calculus.

propositions. Consequently such a system of encoding constitutes an appropriate null-hypothesis against which to compare other theories of the encoding of mental images. When a theory is proposed we can ask: Can it explain anything that a quasi-linguistic theory would not be able to explain (and vice versa)? If not, nothing is gained by accepting the proposal and a great deal is lost, such as the entire apparatus of inference as developed in formal logic and continued in non-classical logics such as the non-monotonic logics studied in artificial intelligence.

4) *There is nothing special about the representations underlying visual imagery – they are the same as representations for verbal or other forms of reasoning.* Putting aside the difficulty of distinguishing different “types of representation” there appears to be every reason to think that *something* is special about the sort of reasoning that is accompanied by the experience of mental imagery – something that distinguishes it from other forms of reasoning. The relevant question to ask about some particular proposal for what is special about mental images is not whether it comports with our intuitions, but whether it can be empirically sustained. And here I do claim that every concrete proposal I have seen of what constitutes this special ingredient that is present in the case of mental images and absent from other forms of thought has been either demonstrably false or conceptually ambiguous or incoherent. The proposals have typically been along such lines as that images are picture-like and “preserve the metrical properties of the objects they depict.” As I have argued (Pylyshyn, 1981), such claims have invariably been presented in what amounts to an intellectual shell game, in which images are claimed to *have* metrical properties or to be pictures when the theory needs to explain certain metrical correlates of represented magnitudes (such as the longer time it takes to scan greater image distances), and merely to *represent* metrical properties when the literal picture view seems false or empty. The difference between *having* metrical properties and *representing* them is fundamental: the first is a claim about the form or of the physical property of the system of codes used to represent magnitudes such as distance, while the second is simply a claim concerning what properties in the world can be represented (i.e., it’s a claim about the representational capacity of the system of codes). The second is obviously much weaker than the first since, for example, it is fulfilled universally by human languages (since all languages have at least some names for magnitudes, such as the numerals). The first claim (that images have metrical properties) can be taken either as a formal mathematical claim (i.e., the system of codes has a formal property that supports the metrical axioms), which is often put in terms of the claim that images are encoded in terms of analogue representations, or as a literal claim that images are laid out in physical space in the brain. Recently certain image-as-picture theorists claim to have obtained neurophysiological evidence supporting the literal interpretation of the spatiality of mental image – they claim to have come close to finding pictures in the visual cortex. Whether this is (a) true and (b) of any consequence to the theory of mental images remains moot. I will examine this issue later.

5) *The visual system is not involved in manipulating and interpreting mental images.* The claim that imagery and vision are closely linked and use the same mechanisms may or may not be true, or even meaningful, depending on how broadly one takes the notion of “visual system.” If by “visual system” one means any process concerned with interpreting visual information, including the processes involved in allocating attention and recognizing visual objects, then the claim is almost certainly true. But it is true for the uninteresting reason that, as we saw in Chapter 2, much of what happens in this extended sense of vision is a form of reasoning so it will naturally also apply to reasoning using mental images. If, however, the claim is that what I have called “early vision” – the part of the visual system discussed in Chapter 2 that is unique to vision and is cognitively impenetrable – then there is good reason to doubt that these mechanisms are involved in the examination of mental images. I examined some of the evidence for this claim in Chapter 6.

6) *The so-called “imagery debate” is over and one or the other side is the clear winner.* The trouble with this statement is that although there has been a great deal of discussion about the nature of the representations and mechanisms involved in mental imagery, such discussions hardly qualify as a debate since there are not two (or more) well-defined sides, due largely to the fact that most theories of mental imagery rest on undefined (and perhaps undefinable) notions. The “debate” so far as I understand it, is not between two theories or even two classes of theories of mental imagery. Rather it has been about whether particular proposals that have been put forward have any empirical validity (or in some cases, conceptual

coherence). But the more general debate has failed to define the most basic notions involved in the argument. For example, some researchers supporting the picture theory position (e.g., Kosslyn, 1994) have claimed that image representations differ from other forms of representations involved in reasoning because image representations *depict* rather than *describe* their referent. This is a very seductive way of putting it and indeed the notion of “depicting” has gained considerable currency in psychology. However the notion, as it is used by image theorists, is empty. While there is at least some formal way of characterizing what is involved in “describing” (in terms of, say, Russell’s theory of definite descriptions and Tarsky’s model-theoretic semantics), so that one can say what it is for a sentence-like structure to describe a situation, *nothing* is known about the relation of “depicting,” though we are pretty sure that it is not a relation understandable in terms of projective geometry. The term is used merely to emphasize that image representations are different from descriptions and are more like pictures than like sentences. But if one were to ask *in what way* an image is more like a picture than like a description, one would find no answer forthcoming. Moreover it is frequently claimed that the relation of “resembling” rather than the semantic relation of “referring” is the central one for representations involved in imagery, but “resembling” remains an opaque concept, as many philosophers have pointed out (Goodman, 1968). It is not an objective relation but one that can be understood only in relation to an intelligent agent who, given relevant background knowledge, perceives a similarity between two things.

The focus of the discussion has changed in the past decade and there has been a great deal more evidence brought into the discussion, especially evidence from clinical neurology and from various forms of brain imaging (such as PET, MRI, fMRI) and recently also from an intrusive technique of disabling part of the brain using transcranial magnetic stimulation (rTMS). Yet this increase in the empirical base, welcome though it is, cannot offset the fact that the questions and options under discussion continue to be ill-formed. No matter how much objective reliable evidence is introduced, the “debate” cannot be resolved until the nature of the claims is made clear. There is, at the present time, an enormous gap between the evidence, the models, and the claims being made about the real nature of mental images. In what follows I will trace the course of some of the points of contention between those who advocate “depictive” theories of mental imagery, who I shall refer to for brevity as picture-theorists, and those who oppose this view. The opponents of this view are often referred to as “descriptivists” – a term that is misleading both because these writers generally do not claim that images are merely descriptions and because, strictly speaking they are not presenting worked-out theories so much as attempting to set conditions on an adequate theory. But first I must take a detour into some background matters in order to introduce some terms and distinctions I will need later.

7.5.2 What are some constraints that should be met by a theory of mental imagery?

I have already alluded to some ideas that have been presented concerning how images may differ from representations underlying thought not accompanied by the experience of seeing. In (Pylyshyn, 1978) I speculated on some properties that an adequate form of representation for mental imagery might involve. A tentative set of constraints on representations that might underlie images may include, for example (where for “image” read “whatever form of representation underlies mental imagery”):

1. *Images contain information about the appearance of things*, so they use the vocabulary of visual properties (e.g., color, brightness, shape, texture, and so on).
2. *Images contain information about the relative location of things*, so they use the vocabulary of geometrical relations (above, inside, beside, to-the-right-of, and so on). Indeed, there is reason to think that representing spatial properties is a more fundamental characteristic of what we call images than is representing appearance properties (Farah, Hammond, Levine, & Calvanio, 1988).
3. *Images represent individual things*; they represent *token* individuals (things or objects). The content of an image may also ascribe types to these tokens (i.e., it can represent an individual X as a Y – e.g., “the thing on the desk is a book”), but this always involves attributing the category membership to a represented individual.

4. *Images lack explicit quantifiers.* Images are not able to express such assertions as that *all* things in an image are X's, or that *some* of the things in the scene are Y's and so on, although they can represent some or all individuals in the image as being X's. Representing a content that is quantified (there is an individual – unspecified – that is Y, or all individuals are Y's) can only be accomplished by adding symbolic tags that the person takes to have the meaning of a qualitative – which is to say, an image can only represent quantified or generalized properties by means that are essentially non-pictorial.
5. *Images lack explicit disjunctions.* Images are not able to express such assertions as that either individual X or individual Y is a (type) A, or that individual Z is either an X or a Y. The closest one can come to this is to have two images, one with only X and one with only Y.
6. *Images lack explicit negation.* They cannot carry the information that there are no X's in the image or that none of the X's are As. Rather, negation is expressed indirectly by the absence of certain information (together with the assumption that all relevant things are included).
7. *Images provide access paths* that make getting from one item or property to another more direct for some sets of items and properties than for others. Relations such as *adjacent* may have a privileged position in terms of providing more direct access paths than, say, *same-size-as*, so that it is easier to get a locus of processing from one individual to an individual that is represented as adjacent to it, than to another individual that is the same size.
8. *Images may lend themselves to certain kinds of transformations* in preference to other transformations. Without assuming any particular format for images, it might be that carrying out certain operations on them is more natural than other transformation. As I suggested in section 6.3.4, this may have to do with how various properties are encoded (e.g. orientation may be encoded independently from shape), it may have to do with computational complexity issues or other general (non image-specific) constraints on transformations, or to task requirements, or to a habit of considering the consequences of a certain change by imagining that you were performing the change in the imagined world. Also it may be simpler to carry out certain operations in certain sequence, for example in order to compare two shapes that differ in their orientations it might actually be computationally cheaper to actually go through the computation of representations of the shapes at intermediate orientations, or to imagine a sequence of increasing length of a line in order to judge what would happen if you extrapolated an arrow towards some points. None of these constraints need be principled or attributable to the architecture of an imagery system, as I argued in Section 6.3.4.
9. *The information about individuals in an image can be associated with individuals in a perceived scene.* This was the point I made earlier (section 7.2.2) about the inheritance of spatial properties from perceived scenes. We can think counterfactual thoughts (suppose that ...) about particular individuals that are indexed in a scene, and the thoughts can be of the form "Suppose that the end of the line is at the location of *this*," where the locative "this" picks out an actual thing or feature in the scene being observed. This simple assumption allows us to explain the apparent ability to project an image onto a scene so that the combined image-and-scene behaves in some (limited) ways like a new hybrid scene.

This list could be extended with a little thought. But notice that these proposed characteristics of mental images are quite different from those proposed by picture-theorists (e.g. the characterization of a "depictive" representations quoted in section 6.4). In fact, none of the ideas concerning mental imagery that have surfaced in cognitive science take these desiderata seriously. Mental pictures do have some of the properties on this list, but they have very serious drawbacks, as we have seen. Because images function in reasoning, they either have to have the properties that some people have recognized to be essential properties of any form of representation underlying reasoning (see, for example, Fodor, 1975; Fodor & Pylyshyn, 1988), or else they require an additional stage of translating the imagery form of representation into a form that does have these properties. Of course the second of these is assumed by picture-theories; the "mind's eye" performs the function of converting pictures into thoughts. But given the conceptual and empirical problems faced by theories that assume visual re-interpretation of images, the approach that requires the image representations to have these properties in the first place has much to recommend it. This approach makes

a clear distinction between the information explicitly in the image and the implicit information that can be inferred from the image. The information in the image is then assumed to already be in some form of symbol structures, as in a language of thought or mentales.

The only theory I am aware of that deals with this aspect of reasoning from images, and that appears, *prima facie*, to have some properties listed above, is a system of formal representation proposed by (Levesque, 1986). Levesque describes an expressively weaker, but more efficient, form of logic that he refers to as a “Vivid Representation.” This proposal has the merit of recognizing that we can have forms of representation that are more limited in what they can express but have the special feature that they allow certain conclusions to be drawn rapidly – essentially by a form of pattern-matching. Like images, they do not allow one to directly express negation (e.g., the only way that they can represent the proposition “there are no red squares in the scene” is by representing a scene that contains no red squares), or disjunction (e.g., they can only represent the proposition “the squares are either red or large” by allowing two possible representations, one with red squares and one with large squares, to both be treated as true), and they do not allow quantification (e.g. they can only represent the proposition “all squares are red” by explicitly representing each square, however many there are, and showing each as red). Like images, they can not express the fact that there are 5 objects in the scene, except by representing each of the objects, of which there would have to be 5 in all). I had informally proposed a similar set of ideas in speculating about what might be special about representations underlying imagery as opposed to representations underlying thoughts about more abstract topics (Pylyshyn, 1978). These are, admittedly, small steps towards a formalism for the conceptual content of images. They do not suggest why such representations should be accompanied by the experience of seeing, although they do have the virtue of being limited in some of the same ways that images are.

Perhaps more importantly, none of the sorts of representations that have been proposed for mental imagery explain why reasoning accompanied by the experience of mental seeing should have some of the other properties observed (such as the mental scanning and the image size results and others described in Chapter 6). For that we need to assume, at the very least, that certain sorts of tasks *invite* (even if they do not require) people to simulate what it would be like to see certain things happen, and that in doing this people are able to draw on various cognitive and psychophysical skills, such as the ability to estimate time-to-contact and to generate actual time intervals based on such estimates. It also seems that when the task in some way concerns appearances, such as shape or other visible properties (as when we are working on a problem concerning geometrical diagrams) then we have a tendency to simulate drawing on a sheet of paper and we report what we would see in that case, but the content of what we report is derived in ways that themselves are not available to consciousness and have nothing to do with the visualization we experience. At least this is an alternative we must not discard simply because it violates our intuitions.

8. SEEING WITH THE MIND'S EYE 3: VISUAL THINKING

8.1 Different “styles” of thinking

One of the most widely accepted ideas – at least in the mind of the literate public – is that there are different styles of thinking and that these differing styles are most clearly characterized in terms of whether people are “visual” or “verbal” (or sometimes “abstract”) thinkers. There is little doubt that people do differ in a number of ways with respect to their habitual or preferred styles of thought and their approach to problem solving. There is surely also something to the observation that some people tend to think in a way that is in some sense more “visual” in that their thoughts may be accompanied by visual-like experiences. The problem is in spelling out this difference in a way that takes it out of the realm of personal experience and connects it with a scientific theory. Describing some people’s style of thinking as “visual” implies that vision is used in thought that is devoid of actual visual inputs, i.e., in thought that is not augmented by visual aids such as diagrams, tables, and so on. One sense in which thought can be visual is by having visual content, and thought can have visual content in several different ways. One way is that a thought can be about the appearance of something, as when we think of what something looks like (“It looks like a letter D rotated counterclockwise by 90 degrees and attached to the top of a J”). Another, discussed in some detail in Chapter 5, is that a thought can have particular perceived things as its direct object, as when we think, “*this* thing is red.” The jury may still be out on the precise role(s) that vision plays in mental imagery but, as we saw in the previous chapters, we have good reasons for at least discounting the view that imagery involves visually examining a picture or some other world-surrogate inside the head.

But if thought does not consist in examining mental pictures, neither does it consist in listening to mental sentences in an inner dialogue, as introspection suggests. Here we come, once again, to the conflicting demands of one’s conscious experience and those of a scientific theory that has explanatory power. It is to this conflict that I now turn.

8.2 The form and content of thoughts: what we think with and what we think about

8.2.1 The illusion that we experience the *form* of our thoughts

Ever since the use of mentalistic terms (such as “know”, “believe”, “think”, “want” and so on) became once again permissible in psychology and philosophy (after a long dry period of behaviorism) people have found it completely natural to assume that we have conscious access not only to the content of our thoughts, but also to the form that they take. Thus we find it natural to suppose that our thoughts take the form of either inner dialogue (thinking in words) or of imagining a visual scene (seeing an image in our “mind’s eye”).⁶⁶ In fact this homily has been translated into what is known as the “Dual Code” theory of mental representations (which was developed most extensively in the work of Paivio, 1986). A major motivation for the dual code view leans heavily on the fact that most people – especially great thinkers like Einstein,⁶⁷ Maxwell, Faraday, Helmholtz, Galton, Watt, Tesla and others (see, Shepard, 1978a) – maintain

⁶⁶ Notice that when you experience something, you invariably experience it as something *sensory*. Try imagining an experience that is not the experience of sensing something. It is no accident that the content of experiences is that of perceiving some (actually or possible) sensory world. Even inner feelings like pain or queasiness, or emotions such as anger, are experienced as perceptual sensations (in fact the James-Lange theory of emotions equates emotions to perceived bodily action-states). Given this universal property of conscious experience it is no surprise that when we experience our thoughts we experience them as a seeing or a hearing: What else *could* we experience them as?

⁶⁷ (Shepard, 1978a) quotes Einstein’s prologue to Planck’s book (Planck, 1933) as saying, “There is no logical way to the discovery of these elemental laws. There is only the way of intuition, which is helped by a feeling for the order lying behind the appearance.”

that their thoughts are “devoid of words” (Shepard, quotes Einstein’s prologue to Planck’s book, Planck, 1933, as saying, “There is no logical way to the discovery of these elemental laws. There is only the way of intuition, which is helped by a feeling for the order lying behind the appearance.”) Then the tacit assumption that thoughts are represented either in words or in pictures leads directly to the conclusions that their thoughts are in pictures and that it is these sorts of pictorial thoughts that are the source of creativity (I will take up the question of the relation between mental imagery and creativity in section 8.5 below).

Of course one also allows for the possibility that a person might think in terms of acoustical or tactile or other sensations, even though these may be less central for most people. But what about the possibility that the form of thoughts is not only largely unconscious, but is something that never could be made conscious. Many people have assumed that such an idea is pretty nearly incoherent (see, for example, Searle, 1990). Notwithstanding the widespread influence of Freud’s idea of the unconscious, it is still generally assumed that thoughts are the sorts of things which, although they might occasional be unconscious, nonetheless in principle *could* be made conscious, and moreover if they were conscious they would be experienced as something we hear or see or otherwise sense. Indeed, Western philosophy has generally made the awareness of one’s thoughts the basis upon which one ultimately justifies the ascription of particular contents to them: You know what your thoughts are about because they are *your* thoughts and you have special privileged access to them through your conscious awareness. If that were not the case, the argument goes, there would be no basis for ascribing one content as opposed to some other content to thoughts (for a discussion of why we need to appeal to contents at all, and for a different view of how we might ascribe content, see Pylyshyn, 1984a).

I will not quarrel with the idea that we have a privileged access to the content of our thoughts, nor will I even try to define what it means for thoughts to be conscious. Nevertheless, I do claim that there is every reason to believe that (a) the form of one’s thoughts is something that has to be inferred indirectly in the same way that one infers the form of matter in physics and chemistry, without prejudging the scientific issue based on how we experience our own thoughts, and (b) what one is aware of – the form and content of one’s conscious thoughts – cannot be what plays the causal story in reasoning. In other words, what we are aware of, such as the inner dialogue of one’s thoughts or the pictures one sees in one’s “mind’s eye” cannot be what is responsible for people having the thoughts they have, of making the inferences they make, and of representing the understanding that they have (of, say, the meaning of a certain sentence or the contents of a certain scene). The reason for maintaining this is that the content of one’s experience is demonstrably insufficient to encompass the content of our thoughts. The sorts of things of which one is aware, such as the words or sentences of the “inner dialogue” or the “mental pictures” one imagines, greatly underdetermine what one is thinking at the time one has those experiences. Consequently something else must be going on, other than more words or more images. Or so I will argue in the next part of this chapter.

8.2.2 Do we think in words?

Consider an example where one appears to be thinking in words. As I type these sentences I think to myself, “I’d better hurry and finish this section or I will be late for my meeting.” Now this is a pretty innocuous thought with little apparent hidden meaning. But look at it more closely. If I “said” that sentence to myself in my inner dialogue, I meant something far more than what appears in the sequence of words. I knew which particular text on my computer screen I meant when I thought “this section”, I knew how much time would have to pass (roughly) in order for it to count as being “late” for a meeting, I knew which meeting I had in mind when I thought “my meeting,” and I knew what counts as “hurrying” when typing a section of text, as opposed to running a race. And for that matter I knew what “I” referred to, although the sentence I imagined thinking did not say so. In fact sentences *never* say all that their speakers mean. Sentences, as elements of discourse, follow such Gricean Maxims (Grice, 1975) as “make your statement as informative as required but not more informative than required” (in other words, don’t express what you think your hearer already knows) or more generally a statement in a discourse is assumed by all parties to be relevant and to be as informative as appropriate. And sentences follow such maxims just as dependably in inner dialogue as they do in external conversation. But if the sentences do not express all that I know or intend, then what I know or intend must take some other form – a form of which I have no conscious

awareness. It is no help to say, as one might in discussing an actual overt conversation, that the hearer of the sentence infers the missing parts, because in inner dialogue the speaker and hearer are the same. And if the speaker knows something that remains unexpressed in the sentences of the inner dialogue this just shows that the inner dialogue is not doing the work one assumed it was doing. The imagined inner dialogue leaves many unstated things to the imagination of the inner speaker and hearer whereas, as Steven Pinker puts it (Pinker, 1997, p70), the “the ‘language of thought’ in which knowledge is couched can leave nothing to the imagination, because it *is* the imagination”: there is nowhere else for the unexpressed parts of the thought to hide.

The problem of expressing the entire content of your thoughts in sentences is even deeper than might appear from this discussion. It was already known in the early history of logic that sentences are too ambiguous to serve as the vehicles of reasoning. For this reason, logicians had to devise more precise formalisms in order to express in a different way the distinct meanings that a sentence could have (e.g., mathematical systems of symbolic logic, such as the predicate calculus). For example sentences like “Every man loves a woman” can express at least two distinct senses (one in which for each man there is some woman that he loves, and the other in which there is a woman such that every man loves her) thus making it necessary to introduce such syntactic mechanisms as quantifiers and brackets in order to express these distinct meanings. But in addition to such syntactic ambiguities, both words and phrases cut the world up more coarsely than does thought. There are many concepts for which there is no corresponding a word (though presumably for many of them there *could* be such a word). But, even more seriously, one can have thoughts when one is perceiving something, whose contents cannot be expressed in words, not even for one’s own private purposes. The outstanding case of such thoughts is one that we have already encountered in the last chapter: they are thoughts with a demonstrative (or indexical) component. I can, for example, think a thought such as “This pencil is yellow” where I am able to pick out an individual and claim of it that it is a pencil and that it is yellow. The object that my visual indexing system picks out is the very object about which I am having the thought, and forms part of the content of my thought, yet it cannot be expressed, linguistically or otherwise. And for that matter, neither can most of the properties of the object I am seeing and which can enter into my thoughts. For example, I can have the perfectly clear and well-formed thought “*This* is the *same* color as *that*” where the content of my thoughts in some important sense includes the color as well as the meaning that the two *things* I have mentally picked out are the *same* color. Yet I cannot express this thought in language – not because I don’t know the correct words, but because I needn’t even have a category or concept for an important part of what I am thinking, namely what is being referred to by the demonstrative “that,” and therefore for its color! Some thoughts, in other words, can contain *unconceptualized contents* (as we saw in Chapter 5, where I discussed the notion of an index that connects parts of a thought with parts of the world). This, in turn, means that the grain of thoughts, or the possible distinctions among their contents, is even finer than those of one’s *potential* linguistic vocabulary (assuming that one’s vocabulary is necessarily confined to the things for which one has concepts).

The notion that language cannot be the medium of thought because of inherent ambiguity and instability in relation to the specificity of the contents that it expresses, has been noted by many other writers. (Block, 2001) has recently argued that there is also an inherent difference in grain between thoughts and experiences – we can have visual experiences at a finer grain than the grain of our thoughts. (Sperber & Wilson, 1998) make a similar point. They argue that there must be many more concepts than there are words and that, unlike concepts, the meaning of a particular word token may depend on many pragmatic factors. (Fodor, 2001) also makes the same point in arguing that language only approximates the compositionality and systematicity required of thought (see also the discussion of systematicity and compositionality in section 8.2.4).

8.2.3 Do we think in pictures?

Now one might well concede that sensory contents can be finer grained than verbal ones and thus that we can represent properties visually that we cannot describe verbally. This suggests that mental states (thoughts) must include sensory contents as well as verbal content, which is the basic premise of the dual code view of mental representations as well as the “perceptual symbol system” idea championed by

(Barsalou, 1999). In the case of visual properties, we might postulate that these could take the form of visual mental images. But visual images have the same problem of indeterminacy as do sentences. Just as the idea that we think in sentences is inadequate because the bulk of the information remains elsewhere, so mental pictures face the same indeterminacy problem. Consider a simple example in which a visual image allows one to solve a certain problem. People appear easily to solve what are called three-term series problems by imagining that the objects described in the problem are located in an array where the spatial relations among them represents their relative standing on some measure. A typical problem goes like this. “John is taller than Mary but shorter than Susan. Who is tallest (/shortest)?” (Instead of “taller” one can substitute “smarter” “richer” and many other such formal relations.) To solve this problem, all you have to do is place a tag representing John at a fixed location in an image, then when you hear that John is taller than Mary you locate a tag for Mary below the one for John in a vertical stack and when you hear that John is shorter than Susan you locate a tag for Susan above the one for John to yield an image such as Figure 8-1. You solve the “who is shortest” problem by finding the lowest tag in the image.

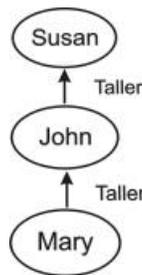


Figure 8-1: Elements in the three-term series problem may be imagined as located in a vertical array and the answers to the problem may be obtained by merely examining the array.

(De Soto, London & Handel, 1965) refer to this way of solving problems as using “spatial meta-logic” (see also Huttenlocher, 1968). Even though this example is extremely simple it has inspired a great deal of research (for example, the exact wording has been shown to have a strong effect, which suggests that the linguistic processes – translating from sentences to some other form of representation – may account for why problems worded in one way are easier than ones worded in another, Clark, 1969). But even here one might ask whether other cognitive representations (knowledge, inferences, etc) might be involved, besides those in the image and/or the sentences experienced by the person solving this problem. A moment’s thought will reveal that there is much more going on than just inspecting the image. Right at the start, in hearing the sentence “John is taller than Mary but shorter than Susan” the hearer must figure out what the missing parts of the sentences are: the subject and verb of the second clause are missing and must be restored in the course of the grammatical analysis of the sentence. In fact by some analyses even more words are missing in the surface structure (“John is taller than Mary but shorter than Susan” means “John is taller than Mary <is tall> but <John> <is> shorter than Susan <is short>”). This involves appealing to grammatical rules (in this case, deletion rules) – the processing of which is never conscious. Following this grammatical analysis there is still the question of how the problem statement is converted into “mental drawing” instructions. Notice that in order to know that a vertical array is an appropriate structure to use in this problem, the person must already have done some reasoning. Only relationships that have the formal property called “transitivity” are candidates for such a structure. If the problem had been about the relation “likes” then the structure would have been inappropriate (since “Mary likes John” and “John likes Susan” does not entail that “Mary likes Susan”). How do subjects solve all these preliminary problems? Through what *conscious* imaginal or verbal steps do they go? Obviously they do not do it in language since this is about how they understand the language, and they don’t do it in pictures since it is about deciding what pictures to construct and how to interpret them.

There are also many properties of the imaged array that are assumed in this way of characterizing the problem-solving process. Where do these assumptions come from and how are they justified? For example, according to the account given, a symbol for Mary (call it *Mary*) is placed below *John* in a vertical

stack. Next, *Susan* is placed above *John*. This appears also to locate *Susan* above *Mary* in the stack. Why? For that to be true two further things must be true of the image. One is that it must be the case that some operations on the image do not change certain relations that are already there. In the case of an array written on a board, when you add an item above a stack of two items already there, the two items generally keep the same relations as they had before the addition. That's at least partly because the board is rigid and some geometrical relations on a rigid board remain fixed when new ones are added. But even this is not always the case. For example the relation between two objects of being "directly above" or "next to" is changed when another object is inserted between them. Thus if the instructions had led you to place *Mary* "directly below" *John* and the next instruction also led you to place *Susan* "directly below" *John*, the relation between *John* and *Mary* would be changed (or become indeterminate) as a result of the new addition (*Mary* may no longer be "directly below" *John*). (For more examples, see section 8.4).

While this seems like a trivial matter and easily corrected, it turns out to be the tip of a very large iceberg called the "Frame Problem" (see, e.g., Ford & Pylyshyn, 1996; Pylyshyn, 1987). The problem arises because when one carries out actions in one's mind, as opposed to actually executing actions on the world, the problem of determining from what one knows, what will change and what will remain fixed is in general intractable. That's because what can change is whatever may be relevant to the action, and the general problem of relevance is itself intractable; any belief can be relevant to any action so long as there is a possible chain of reasoning that can connect them. Such a chain always exists since one can in principle have beliefs that conjoin any pair of beliefs. One could have the belief Q that "if P_j then P_k " for any possible pair of beliefs P_j and P_k , and so if P_a is relevant to action a , then there may be a chain from any belief P_j to action a . For example, supposing that one has the belief (P_1) that to leave the room (i.e., to be located outside the room) you should open the door, and that to open the door one must be close to the door (P_2). If one also has the apparently unrelated belief (apparently unrelated because it does not involve any of the concepts of the first belief, such as door, inside, etc) that there is a security system triggered by movements which locks all means of egress (P_3) then the link between P_1 and the goal of being outside the room is blocked. This information is implicit in one's knowledge, but inferring it could mean checking every belief in one's entire database of beliefs – an intractable task given the nearly unbounded size of one's entire belief set (for more on this "Frame Problem" see the essays in Pylyshyn, 1987).

Even if you could correctly solve the problem of whether an already-present relation in the image changes or remains unchanged when an action (including checking the image for the presence of some property) is performed, there is then the problem of interpreting the resulting image. Why does the shape and size of the ellipses not enter into the conclusion? What determines which relations are relevant and how to read them off the image? Also in this example the same meaningful relation ("taller") occurs in different geometrical guises. While the diagram shows *John* being taller than *Mary* and *Susan* being taller than *John*, it does not show that *Susan* is taller than *Mary* in terms of the same geometrical relationship (e.g., in that case they are further apart and there is an intervening item in the array). Reading off this relationship requires knowing that the presence of an intermediate item does not affect the relationship between the two items in question (unlike the relationship "adjacent to"). This is a property that is not represented in the image or anywhere else in consciousness. In each of these examples, reasoning is involved that is not represented in the diagram, nor is it contained in an inner dialogue. The point of all this is that the things of which we are aware – the words and mental images – are never sufficient for the function attributed to them. In every case, more is going on. And what more is going on is, at least in certain cases, patently not expressible as a sentence or a picture. Yet despite this important point, it is nonetheless also true that pictures can enhance thinking in important ways that I shall take up in section 8.3 because vision, when directed to real diagrams, often provides operations that can be used to draw inferences more simply than by using rules of logic. This is especially true when reasoning about spatial properties, as in geometry.

Visual thinkers are people who think in terms of what things look like. It is perfectly reasonable to say that some thoughts are about appearances, just as it is perfectly reasonable to say that some sentences are about appearances. Sentences such as "he looks tired" or "she looks good in her new hairdo" or "the big red ball is behind the blue door" are in part about appearances. Terms like "red" describe a visual property.

But these are all properties of things being described, not of sentence or of thoughts. It is the content of the description that is visual, not the form itself.

8.2.4 What form must thoughts have?

(Fodor, 1975) presents a tightly argued case that thought must be encoded in what he calls a “language of thought” or LOT. Of course LOT cannot be a natural language, such as English for the reasons presented above. Also, of course, a great many organisms do not have any language, as is the case with pre-linguistic children and non-linguistic organisms like higher primates, and yet are clearly capable of thought. Any vehicle of thought must have certain properties. One of these properties is *productivity*. Since the number of thoughts we can have is, in principle, unbounded (except for practical considerations such as one’s mortality and limited range of experience), thoughts must be constructed from simple elements, called concepts (as Humboldt put it, they are capable of “infinite use of finite means”⁶⁸). Moreover, the meaning of complex thoughts must be derived from the meaning of its constituent parts, which means that thoughts must be *compositional*; all the meaning of a complex thought must come from the meaning of its parts, together with the rules of composition (or syntax) of LOT, it cannot come from any other source. Even more important, thoughts must have the property that (Fodor & Pylyshyn, 1988) call *systematicity*. What this means is that if an organism is capable of thought at all it must be capable of having a set of related thoughts. If it can think, say, “Mary hit the ball” and it can think “John baked a cake” then it can also think the thoughts “John hit the ball” and “Mary baked a cake” and even the thought “John hit the cake” and “Mary baked the ball”. Of course it is unlikely to think the latter because these are bizarre events, but the point is that the system for encoding thoughts encodes complexes from simples and once that system is in place and the constituent concepts are available, the capacity to form the complex thoughts is inherently there.

In (Fodor & Pylyshyn, 1988) we also argued that inference requires compositionality of the system of representation. Rules of inference are schemas; they tell you how to draw a conclusion from premises by recognizing a structured representation and they apply regardless of the complexity of the premises. For example, if you have a thought with the content, “It is dark and cold and raining” you are entitled to conclude, “It is raining.” This follows from the rule of conjunction elimination: from P & Q infer P (or infer Q). In this rule the P and Q can be arbitrarily complex expressions. For example, Q might actually be “R and (S or T)” in which case one would be entitled to infer from “P and (R and (S or T))” that P or that “R and (S or T)”. So take a thought such as the one given earlier. Since any intelligent creature could infer from the thought “it is cold and raining” that “it is raining” it must also be able to infer from “it is dark and cold and raining” that “it is raining”. In other words there is systematicity in what you are able to infer from complex thoughts: If you can make one sort of inference, you are thereby also able to make other sorts of inferences (especially simpler ones as in the example here). None of this depends on exactly how the beliefs are encoded except that they must have parts that determine the meaning of the whole and these parts, in turn, are what determine what can be inferred. These sorts of considerations are what lead one to the view that whatever form thoughts may take they are bound to meet the conditions of systematicity, from which it follows that they are bound to have constituents and to exhibit compositionality. This makes them rather more like a language than a picture or any other fused form, such as proposed by proponents of the “connectionist” approach to modeling mind (for a more detailed exposition of this point see Fodor & Pylyshyn, 1988).

Notwithstanding the sort of argument presented above, the requirement of compositionality does not prohibit there being analog or other non-linguistic components in representations. For example, there is no prohibition against individual terms in the vocabulary of LOT being drawn from an infinite set, as they might be if they constituted what (Goodman, 1968) calls a “dense symbol system.” While such arcane symbol systems are not prohibited, it is still an open question what would be gained from assuming them. We

⁶⁸ This idea was made famous in the early 1960s by Noam Chomsky. For more on the Chomskian revolution in Cognitive Science see: <http://mitpress2.mit.edu/e-books/chomsky>

know, more or less, what can be done with discrete symbol systems (pretty much all of logical proof theory and computer science is about such systems), but there are only hints as to what would be gained by admitting other sorts of symbols into LOT. But one can also augment LOT by adding non-linguistic (or non-conceptual) elements in several ways. For example, there is a different way in which nonlinguistic entities can function in thought; they can provide external elements or models that can be used in reasoning. We are all familiar with the usefulness of diagrams, charts, graphs, and other visual aids in conveying meaning. Before considering the possibility that parts of thought may be carried by non-symbolic means, we need to look at why real diagrams might be useful in reasoning and ask whether those functions can be reasonably obtained from imagined diagrams.

8.3 How can visual displays help us to reason?

8.3.1 Diagrams as logical systems that exploit visual operations

To accept the conditions on the format of reasoning is not to deny that thinking about some kinds of problems can be enhanced by the use of vision – real vision of real displays. Some kinds of problem solving – say proving theorems in plane geometry – appear to proceed more efficiently when we are able to use displays or diagrams as a prosthetic to aid in thinking. Although the mathematician David Hilbert showed that Euclidean geometry using diagrams and based on Euclid’s axioms (as put forward in his “Elements”) is not rigorous in that it makes hidden assumptions (particularly about the existence of points and lines that are drawn according to the compass-and-straightedge requirement), it is difficult to imagine proving a theorem in plane geometry without drawing a figure. But consider the assumptions that go into some of the simplest proofs from Euclid. To prove his First Proposition, Euclid used one diagram and accompanying text. The proposition says that an equilateral triangle can be constructed on a given line AB (using only compass and straightedge). The construction is obvious from the diagram: Draw a circle with one end of the line as center and then another circle centered on the other end of the line. Then join the point where they intersect to each end of the line. It is an equilateral triangle by construction. The trouble with this “proof,” as many people have remarked, is that it assumes without proof that the two circles *will* intersect – an assumption that does not follow from any of Euclid’s “elements” or axioms.

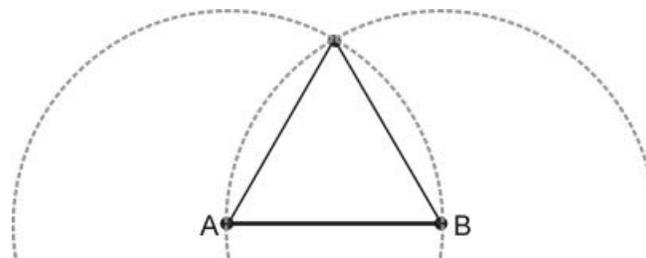


Figure 8-2. Euclid’s First Proposition: an equilateral triangle can be constructed on a given line using compass and straightedge.

The general consensus had been that diagrams can be (or even must be) dispensed with in order to provide rigorous proof of Euclidean theorems. Hilbert provided an axiomatization of Euclidean geometry that had a very non-figural character and did not use geometrical constructions; using these axioms Hilbert was able to make Euclid’s propositions rigorous and free from hidden assumptions. The question of whether diagrams are merely heuristic or whether they can provide a rigorous means of proving theorems has been controversial over the years. But the question has received renewed interest in recent years. A number of writers (e.g., Allwein & Barwise, 1996) have argued that diagrammatic reasoning can be made rigorous while retaining its diagrammatic aspect. Recently (Miller, 2001) has developed an axiomatic system (FG) that treats elements of diagrams as syntactic objects and proves theorems about them that are nearly as simple and transparent as conventional Euclidean proofs. The system has even been implemented as a

computer program (called CDEG – for Computerized Diagrammatic Euclidean Geometry). While this system reasons with syntactic objects which correspond to parts of diagrams, it does not conjecture possibilities based on appearances, thus missing one of the important aspects of human diagrammatic reasoning (at least of the more exploratory sort). Miller was interested in providing a sound formal system, as simple as that based on Euclidean postulates, to back up the informal use of diagrams to explore geometrical relationships, and in this he was eminently successful. Our goal in this section, however, is to examine how diagrams and the human visual system form a more powerful system for reasoning than unaided cognition (or perhaps than reasoning aided by a notepad for writing down formulae or for keeping track of cases).

The visual system is one of our most developed and exquisite cognitive organs and we make use of it in many more ways than recognizing familiar patterns and in guiding our movements. For example, we are able to convert many abstract problems into spatial form, as we do when we reason using Venn diagrams, graphs and other modes of presentation (including the example illustrated in Figure 8-1). Venn diagrams (which are one of the more successful of a wide range of logic-encoding diagrams discussed by Gardner, 1982), allow one to not only illustrate relations among sets or among propositions (the two are interdefinable) but allow one to actually use the diagram for logical reasoning. The Venn diagram representation of propositions, shown in Figure 8-3, illustrates that certain properties of the visual system (e.g., the ease with which it detects whether one region overlaps another or whether some designated element is inside a particular region) can be exploited to facilitate reasoning. Such externalizations exploit the perceptual system (usually, though not necessarily vision) to help recognize patterns. In accepting that vision can play this role we need make no assumptions about the form of our thoughts, only about how we are able to map from perceived patterns to thoughts in the pursuit of intellectual goals. Thinking while seeing allows our thoughts to exploit important properties of space without assuming that the form of our thought is itself spatial. As remarked in Chapter 7, much of the research on mental imagery involves the superposition of mental images onto the perceived world, as a result of which the mental representations themselves appear to have spatial properties (recall the example, discussed earlier, in which an imagined map is scanned while looking at a video screen or a wall).

Venn diagrams and other graphical forms of logical inference are more than just mental crutches; they allow rigorous proofs to be formulated, as (Allwein & Barwise, 1996; Jamnek, 2001) have shown. But for this to be the case, the graphical form, together with the appropriate operations and interpretations, must be isomorphic to normative rules of logic. The study of such graphical forms has been a serious pursuit since at least the time of Ramon Lull, an early 13th century scholar, who invented an influential method, called *Ars Magna*, which consisted of a set of geometrical figures and mechanisms for guiding reasoning. (Gardner, 1982) provides a fascinating discussion of such devices, which include the diagrammatic inventions of Euler, Hamilton, Marquand, Lambert, and somewhat more recently of Charles Peirce, Lewis Carroll and Gerrit Mariè Mes. But diagrams and other sorts of figures can also be useful even when they do not embody a rigorous system of valid reasoning. Indeed, the use of diagrams in proofs of plane geometry is of this non-rigorous sort. The question remains, then, how and why diagrams can be useful as heuristics in such cases. Clearly there is something about vision that provides functions not as readily available in other forms of reasoning. And if that is so, then perhaps mental imagery provides similar functions. It is worth considering, therefore, what vision might contribute to reasoning and perhaps even to creative reasoning.

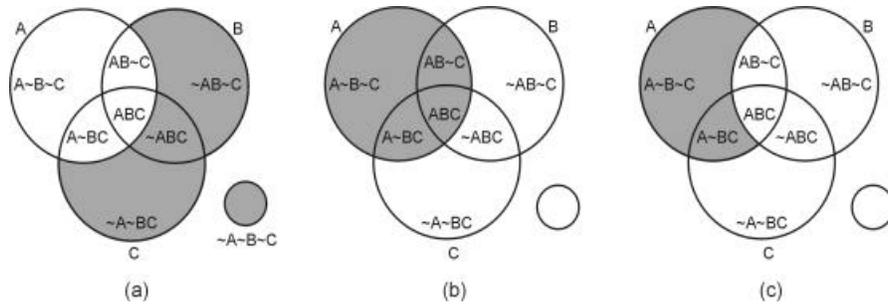


Figure 8-3. Venn diagram representing the propositions A , B , C , their negations $\sim A$, $\sim B$, $\sim C$ and their pairwise combinations. Figure (a) shows A as true, which leaves everything that contains $\sim A$ false and shown as shaded. Figure (b) shows A as false (and therefore shaded), and leaves all the other possibilities true. Figure (c) shows how material implication (denoted $A \supset B$), can be represented, by shading all regions in which A is true and B is false (all regions containing $A\sim B$). To see what is entailed by $A \supset B$ when A is false, shade all areas of (c) containing A that are not already shaded; then we get figure (b) and we see that B can be either true or false. To see what is entailed by A being true, shade all areas in (c) not already shaded that contain $\sim A$. This leaves only the two central regions ($AB\sim C$ and ABC) unshaded and leaves all areas containing $\sim B$ as shaded. So if $A \supset B$ then A being true entails that B is true. (Based on Gardner, 1982).

8.3.2 Diagrams as guides for derivational milestones (lemmas)

Consider the following example in which drawing a diagram makes it possible to prove one of the most important theorems in plane geometry: Pythagoras's Theorem. In Figure 8-4 we see a right angle triangle with sides a , b , and hypotenuse c . To prove that the square on c is the sum of squares on a and b , we begin by drawing a square on side c . Then we extend the sides a and b until they both equal $a + b$ and we draw a square on these sides (the area of this square is $a + b$ times $a + b$). Without going into the individual steps one can readily prove that the original triangle is reduplicated 4 times (verify that each of the triangles in the corners is similar to the original triangle and has hypotenuse of length c , therefore is congruent to the original triangle)⁶⁹. Thus we see that the large square $(a + b)^2$ is made up of the square on c plus 4 triangles. Therefore to get the area of the square on c we subtract the 4 copies of the original triangle that fit between the square on c and the outer square on $a + b$. Since the area of each of those 4 triangles is $\frac{1}{2}ab$, we have the following equation: $c^2 = (a + b)^2 - (4 \times \frac{1}{2}ab) = a^2 + b^2 + 2ab - 2ab = a^2 + b^2$.

⁶⁹ Barwise & Etchemendy (1996) use the same diagram but view its construction differently. They start off with just the triangle and construct a square on its hypotenuse. Then they explicitly replicate the triangle three times and move it into the positions shown in Figure 8-4. The proof then proceeds by showing that these triangles fit snugly in place by using the fact that three angles of a triangle sum to a straight line. Replicating and moving/rotating a triangle are operations that would have little meaning without a diagram.

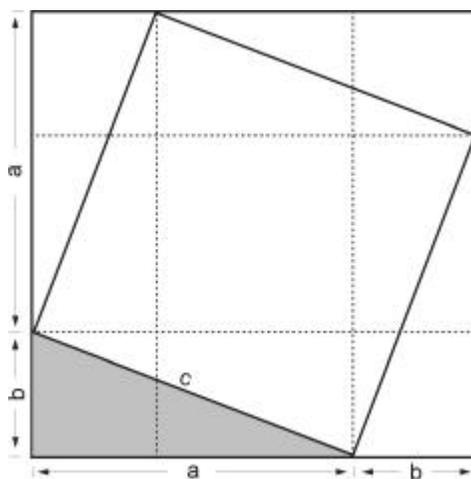


Figure 8-4. Illustration of how construction helps to prove a theorem in plane geometry, in this case the important Theorem of Pythagoras.

This proof, though easier to describe, is not as elegant as some of others that do not use algebra (there are at least 367 published proofs, many of which only require folding and shearing and overlaying parts of the constructed figures, see the references in Dunham, 1994), but it does illustrate the importance of construction in geometrical proofs.⁷⁰ Without drawing the square on c and on $a + b$ the proof would be extremely difficult and in fact would likely have been impossible in Euclid's time. So what purpose do the constructions serve? In Euclid's geometry the constraints on construction defined the rules of plane geometry: problems might be paraphrased as, "using only a compass and straightedge, show that ...". The constraints placed on construction constituted one of Euclid's 5 "postulates." But beyond that, selecting which intermediate figures to construct is like deciding on which lemmas to prove in the course of proving the main theorem. In addition, the visual detection of similarity and congruence (as we saw in Figure 8-4) provides the important guidance in conjecturing lemmas and developing the proof.

The way in which diagrams and visual aids in general help us to formulate and solve problems is far from being understood. The following characteristics of vision are surely important: (1) Vision provides primitive operations for a number of functions, such as shape recognition and the detection of relational properties like the "inclusion" of certain regions within other regions (in fact this particular relational property formed the primitive operation out of which Jean Nicod hoped to build his "sensory geometry", see Nicod, 1970). Primitive detection operations such as these are very important, for example, in exploiting Venn diagrams. These rely on the fact that people are very good at visually detecting relations such as the inclusion of one region inside another, or recognizing that a set of objects is collinear or that a particular point is inside a closed curve and so on (as we saw in the discussion of "visual routines" in Chapter 5). (2) Another important property of vision, which has received considerable attention in recent years, is that it appears to use a strategy of keeping track of where information is located in the world, rather than encoding it in memory, thus in effect providing what amounts of a very large memory. The idea that vision uses "the external world as memory" was argued forcefully by (O'Regan, 1992) and supported by findings of (Ballard et al., 1997). Ballard et al. showed that in carrying out a simple task such as constructing a copy of a pattern of colored blocks, observers encoded very little in each glance (essentially only information about one block), preferring instead to return their gaze over and over to the model figure that they were copying.

In chapter 5 I argued for the general importance of keeping track of information in the world that had not yet been encoded (or conceptualized) and proposed the mechanism of visual indexes (or FINSTs) to allow gaze or focal attention to return to parts of a figure whose properties had yet to be encoded. Thus

⁷⁰ A selection of proofs of the Pythagorean Theorem, many of them animated and interactive, can be viewed at <http://www.cut-the-knot.com/pythagoras/>

although there is now considerable evidence that very little of a scene is recalled from a single glance (Rensink, O'Regan & Clark, 2000; Simons & Levin, 1997) – unless the observer happens to fixate or attend to a particular part of the scene (Henderson & Hollingworth, 1999; Rensink et al., 1997) – yet a great deal of information is potentially (as well as phenomenologically) available. In fact a great deal of information appears to be available in parallel and extremely rapidly (it seems, for example, that pictures of familiar objects can be recognized in less than a tenth of a second as long as there is no requirement for making an immediate response which would otherwise interfere with recall, see Potter, 1975). The visual system appears to be able to obtain access to a very large amount of information in parallel (or nearly so), thus rapidly grasping relations among parts of a figure. (To anticipate the discussion in the next section we might note here that the mechanism of visual indexing can only be exploited when real vision is involved, not when accessing information from “mental images”). (3) Vision routinely goes beyond the information given – a percept is invariably a generalization of the individual properties of a unique stimulus. In fact any recognition of a pattern is just such a generalization: We do not see something as a chair except that we generalize the particular shape in front of us by putting it in the same category as an unlimited number of other shapes, namely the shapes we see as chairs. The naturalness of such visual generalization merits further remark.

8.3.3 Diagrams as a way of exploiting visual generation

8.3.3.1 Representing universal properties in diagrams

When we draw diagrams and examine them to determine whether some general property holds, we do not just rely on whether we detect an instance of that property in the diagram; we often appear to “see” what properties will *necessarily* hold of the resulting construction. For example, if you want to know where the intersection of two lines will be located if they are drawn inside a rectangle according to a certain specification, you have but to draw an *arbitrary* rectangle and then *arbitrary* draw lines in it meeting the specifications and you can quite often see not only the location of the intersection of particular pair of lines that you drew, but also where the intersection must fall for *any* pairs of lines that were drawn according to the given specifications. For example, you can tell that if you draw a line from each of the two bottom vertices of any rectangle to any point on the opposite vertical side, then these two lines will (a) always intersect and (b) the intersection will always lie below the horizontal midline of the rectangle. You can *see* that by just looking at a particular instance, as in Figure 8-5. How you turn a particular instance of a figure into a universal generalization is far from obvious (although one can certainly come up with plausible hypotheses for particular cases). While going from a particular to a universal is no doubt related to how one does abductive reasoning in general, it appears that in this case the visual system is involved essentially. Its involvement, moreover, goes beyond merely recognizing that a certain particular pattern or property is present in a particular instance of the drawing. Visual perception appears to be the source of the hypothetical generalization in the first instance.

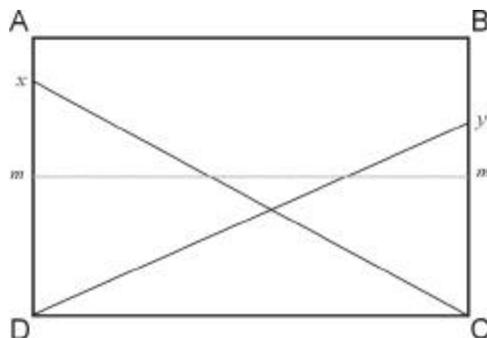


Figure 8-5. You can “see” from this one figure that if lines (Dy, Cx) are drawn from the bottom vertices to any point on the opposite side, the lines will meet at or below the midline (m-m’) of the rectangle in any possible rectangle.

8.3.3.2 How vision generalizes

How does vision make the jump from a particular to a general? One could visually encode general properties by such devices as annotations added to a diagram in various ways (some of them quite natural) to show some general property. Sometimes these annotations are diagrammatic and so do not appear to be annotations. For example, we could represent the infinite family of lines implied by the above drawing in some graphical manner (say as a fan-shaped region, such as in Figure 8-6). But this would still be a token shape, except that we would know to interpret the shaded area as a set of possible lines, much as we would interpret a label. We would thus be relying on an interpretation (which might be quite natural, as in this case) to represent a quantified proposition such as “all lines lying in the region bounded by ...” In this case the representation contains more information (it contains the limits of possible line locations) and would in part be “read” like a description.

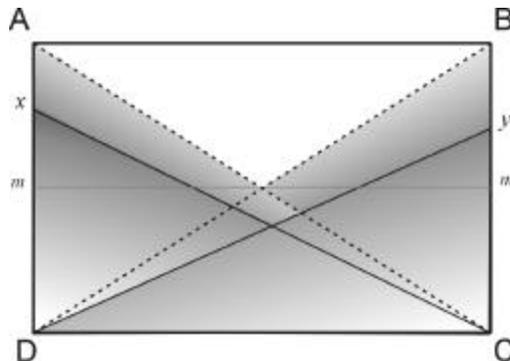


Figure 8-6. One way to think of the class of all lines from D to an arbitrary point on the opposite side is to imagine a fan-shaped area that could be occupied by such a line. But such an apparently pictorial way of representing a class is no different from providing an annotation (perhaps with arrows pointing to particular parts of the diagram) that would be interpreted by the viewer, much the way a symbol would be. In this case, however, the annotation refers to specified sets of locations within the figure.

The use of this sort of implicit annotation (where visual properties are used not to depict a visual or spatial property, but to alter the way other spatial properties are deliberately interpreted by the viewer) is quite common in graphs and is often the only way that noncommittal or vague information can be depicted graphically (see note 7). It is also one of the techniques adopted in many practical schemes for graphing (or “visualizing”) information. Such schemes place a heavy emphasis on selecting the most natural and perspicuous visual properties for conveying various types of secondary or annotation information, such as the use of certain visual dimensions for conveying magnitudes and relationships among magnitudes (e.g., Tufte, 1990). For example, practical schemes consider a variety of image properties, from physical size to brightness and place on the visible color spectrum, as potential dimensions to convey magnitudes and their locations (e.g., on a map). (Norman, 1988, 1991) illustrates how things can go wrong if magnitudes are depicted using a non-metrical visual property, such as texture.

But annotating a figure is not the most general or the most revealing way to view the process by which diagrams can depict general properties by virtue of the way they naturally generalize from particular geometrical properties to classes of properties. The process of going from a particular to a universal in vision is in part the result of how vision itself works; how it parses a complex figure into subparts and how it represents and recognizes patterns. For example, in section 3.1.1 we saw that vision makes essential use of the distinction between accidental and nonaccidental properties in object recognition. Accidental properties are ones that depend on the precise viewpoint and disappear when the viewer makes the smallest movement. For example, two lines in an image could appear aligned or could appear to be coterminous (connected) entirely by accident. They could be two randomly situated lines in 3D that are seen from a particular point of view which just happens accidentally to align them or causes their endpoints to be at the same place on the 2D image (as illustrated in Figure 3-3 of Chapter 3). Yet because the probability of this

happening by accident (i.e., the probability of the 2D image containing two linearly aligned or coterminous line segments when the lines in the world were actually not aligned or coterminous) is vanishingly small and could be detected by a slight change in viewpoint, the visual system always interprets such occurrences as non-accidental (the principles by which the visual system provides nonaccidental interpretations of image features are discussed in Chapter 3). In making such an interpretation, the visual system appears to jump to a conclusion about a universal property from a single instance. Such apparent abductive leaps are quite characteristic of vision and could form the basis for how vision helps us to reason: It provides non-demonstrative inferences on matters pertaining to shape (especially 3D shape which has been studied most).

While it is not viewed in exactly these terms, the study of computational vision – and in particular, the study of object recognition and representation – centers precisely on the problem of how vision generalizes from particulars, or token image shapes, to classes of image shapes. When we “recognize an object,” what we do, roughly speaking, is map the 2D geometrical properties of the token image onto properties that the object *class* possesses. That’s because “recognizing an object” means, in part, to assign the image to a category, and in part it is to provide a representation of the shape that all members of the category possess. I said “roughly” because this is only part of the story. While in a sense vision strips off the properties that are specific to the image token (including what we called its “accidental properties”) in order to focus on the properties of the general object class, vision generally does not throw this information away. It usually represents some of these particulars separately, for example as parameters. This is what various schemes for object representation do; they allow us to factor apart various aspects of the object shape. For example, it may factor out the object’s size and orientation (using some natural axis) and then represent these as separate aspects of the object’s shape. It may also encode the way in which the shape deviates from a simple core pattern. Several methods use what are called “deformable models” to represent a general shape. One common method is based on wrapping a mathematically simple skin over the shape, using a mathematical formalism called a “superquadric” (Pentland, 1986). Many schemes for representing object shapes have been used in robot vision. One of the most widely adopted is the generalized cylinder (or generalized cone) representation, initially proposed by (Binford, 1971) and developed further by (Marr, 1982). This representation characterizes all 3D objects in terms of 3D structures of cylinders whose primary axis can be curved and whose radii can vary across the length of the cylinder. In other words, every shape is described as some set of interconnected and deformed cylinders. This form of representation has been adopted as part of a theory of object-recognition known as Recognition-by-parts, developed by Irving Biederman (Biederman, 1987; Biederman, 1995).

Another example of a particularly interesting core-plus-deformation scheme for object representation is an analysis proposed by Michael Leyton. (Leyton, 1992) provides a mathematical characterization of a particular core-plus-transformation theory. In his theory, an object’s core representation is a highly symmetric shape (for example, a sphere), and the transformations represent various ways that this simple core shape might have been transformed in order to yield the observed shape. The transformations in Leyton’s theory are not merely convenient from the perspective of representing shape, but are chosen to reflect the various ways in which *physical* processes might operate to transform the core shape, hence the representation can be viewed as providing a reconstruction of the object’s history of being deformed. The shape transformations include those produced by physical forces such as stretching, squeezing, twisting, skewing, and so on, as well as other factors such as biological processes like growth and optical processes such as those involved in the projection of light from object to image, which result in transformations such as perspective.

There are many ways of representing shapes in terms of some canonical shape plus some parameters or transformations. For our purposes I wish simply to note that choosing a form of representation, such as the one based on the generalized cylinder form, establishes a pattern of generalization. For example, in the recognition-by-parts technique, based on deformed cylinders, a shape will generalize more readily to objects that have the same relational structure of cylindrical axes than to those that do not, more readily to objects with the same profile of axis diameters than those that do not, and so on. Biederman’s recognition-by-parts system inherently generalizes shapes in just this way, as he showed experimentally by examining patterns of confusion among shapes (O’Kane, Biederman, Cooper, & Nystrom, 1997). In particular, it is relatively

insensitive to size (Biederman & Cooper, 1992), viewpoint (Biederman & Bar, 1999) and rotation in depth (Biederman & Gerhardstein, 1993). To the extent that the theory is a valid description of what early vision computes, it embodies a scheme of visual generalization that functions when we visually perceive patterns, such as diagrams.

8.3.4 Diagrams as ways of tracking instances and alternatives

A diagram is often nothing more than a representation of a particular instance of the givens and of intermediate states of the analysis. It may be a representation of some token situations, rather than of the entire class of situations mentioned in the problem statement. Perhaps in some cases diagrams may be useful, even without the special properties of visual generalization, because they encode distinct instances and allow us to keep track of them.

Consider the following example, discussed by (Barwise & Etchemendy, 1990). “You are to seat 4 people, A, B, C, and D in a row of 5 chairs. A and C are to flank the empty chair. C must be closer to the center than D, who is to sit next to B. Who must be seated in the center chair and who is to be seated on either end?” Here is a straightforward way to solve this problem. First set out the 5 chair positions like this: – – – – –. Next consider the constraints. Since A and C are to flank the empty chair there are 6 cases (where ? indicates the empty chair and – indicates a free or unallocated chair):

Case 1:	A	?	C	–	–	Case 1a:	–	–	C	?	A
Case 2:	–	A	?	C	–	Case 2a:	–	C	?	A	–
Case 3:	–	–	A	?	C	Case 3a:	C	?	A	–	–

Where cases 1a, 2a, 3a are the mirror images of case 1, 2, and 3. Since none of the constraints refer to left or right, the problem can be solved without considering those cases separately. Since C must be closer to the center than D we can eliminate Case 3 (and 3a), which place C further from the center than D. Since D must be next to B we rule out Case 2 (and 2a) because they do not have two adjoining unassigned seats. This leaves Case 1 (and 1a), with B and D assigned as follows:

A	?	C	B	D
A	?	C	D	B

In these remaining cases (or their mirror image) all the stated constraints are satisfied. So the answer to the question is: The middle seat must be occupied by C and one end seat must be A while the other can be either B or D.

While Barwise & Etchemendy present this as a problem that is easily solved with the aid of *vision*, in fact the diagram makes very little use of most properties of vision *per se*. The diagram primarily serves the function of setting out the distinct cases and keeping track of the names that occupy the 5 seat locations. Other than the ordering of the 5 names and their easy access by vision, there is nothing “visual” about the method. Of course a visual figure is an excellent way to encode which position has which letter and it does make it easy to “read off” the contents of the 5 locations. But no property of the pattern other than name and relative (ordinal) location is relevant. Any way of encoding name information and any way of representing ordinal position would do (e.g., this information could have been represented in the tactile modality or as a melody in the auditory/temporal modality). I do not wish to make too much of the modality in which the figure is presented (vision is most likely the easiest if it is available), but it is important for our purpose to see exactly what function the “diagram” is serving. It is allowing us to construct the distinct cases, to apply the problem constraints to each of them, and to access their contents readily. Because the constraints are stated in terms of the location in a row, a linear array is well suited. And because the visual form makes the array easiest to re-access, it may offer an advantage over audition.

Here is another way of characterizing what is special about such a use of a diagram. It is a constructed instance. In such a pure construction (one without symbolic annotations) there are no quantifiers (like “some,” or “all,” or numerical quantifiers such as “some number greater than 2”), there is no negation (the constructed instance cannot represent that something *may not* be the case), and no disjunctions (they cannot

that (a) propositional reasoning is carried out by constructing models and (b) having to deal with a single model results in better performance than having to deal with several models. This appears quite plausible (at least for reasoning about spatial arrangements) when subjects are allowed to sketch the layouts. But what about using “mental models” for reasoning where the model layouts are in the mind? I will return to this question in the next section. But for now we can see from the example that in the case of diagrams sketched on paper, the properties being exploited include the ones discussed earlier: visual recognition of relations like “above” and “to the right of”, the visual capacity to detect relations among disparate objects while ignoring their intrinsic properties (by using visual indexes), and the capacity of the visual system to generalize away from accidental or secondary properties (like the fact that being to the right of and above something entails being to the right of it). In the real diagram case the reasoning proceeds more easily because the diagram provides a rapidly accessible memory that simultaneously contains the given relations among the specified objects and the relations remain fixed as the objects are examined.

8.3.6 Diagrams as a way of deploying visual operations in place of logical inferences

Closely related to the use of diagrams to model space, is the use of spatial displays, together with the operations provided by vision, to carry out inferences concerning spatial properties. Consider the following example. Suppose you have seen a map that contains five objects (e.g., a beach, a windmill, and a church) located as in Figure 6.4 (a portion of which is reproduced as Figure 8-7 below).

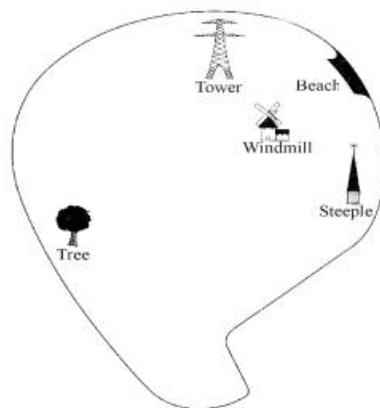


Figure 8-7. Portion of map discussed in Chapter 6, as recalled from memory.

Observers learn this map to criterion so they are able to reproduce the locations of the 5 distinct features. They may have remembered the locations of these features in any of a very large number of ways: they might for example, have noticed the cluster of 4 features at the top right, or they might have remembered the places in terms of units of measurement in relation to the width of the island, or they might have recognized a similarity of shape of the island to the African continent and remembered the map features by associating them with some African countries, and so on. Whatever the mnemonic they use, it must of necessity failed to encode an indefinite number of additional relationships that hold among these 5 places, since it is possible to reproduce the location of the 5 objects accurately without having encoded all the binary or triple relations among subsets of objects.⁷¹ Thus, to take a random example, you might not have noticed that the tower is at about the same latitude as the beach, or that <tower, windmill, steeple> or

⁷¹ Even if you had a so-called “photographic memory” (eidetic memory) your memory representation would be incomplete in very many ways. Very few people believe that accurate long-term photographic memory exists and even if it did, information-theoretic considerations dictate that it would have to be an approximation in any case. Evidence from studies of visual memory show that it tends to be vague in qualitative ways (see Chapter 1, Section 1.4.3), rather than just fuzzy or low-grade the way a poor TV picture would be approximate. There are a number of studies of Eiditikers and few of the claims of detailed photographic memory have stood up to repeated tests. The one principal study by (Stromeyer & Psotka, 1970) has not been replicated and the search for true eidetic imagery remains elusive (Haber, 1979).

<beach, windmill, tree> are collinear or, or that <tower, beech, steeple> or <tower, beech, windmill> or <tower, steeple, tree> form isosceles triangles, and so on. Since there are a very large number of such relationships, the representation is bound to have failed to explicitly encode many of them. Yet despite failing to encode such relationships explicitly, if the representation allowed an accurate diagram to be drawn, it would be possible to notice these and indefinitely many other such relationships by *looking at the resulting drawing*. The missing relationships are implicit in the accurate location of the 5 features. This, in a nutshell, is the advantage of drawing a diagram from what you know; it enables you in principle to *see* any relationship entailed by what you recalled, however sparse the set of explicitly encoded (i.e., “noticed”) relationships might be. Even if such additional relationships might in principle be inferable from what you recalled, making them explicit without drawing the map might be extremely difficult. One might say that in most cases spatial relations are best represented spatially in a diagram in order to exploit the extraordinary capacity that vision has for extracting spatial relationships. But what about the proposal that something very similar occurs even when the figure is not externalized on paper, but internalized as a mental image or “mental model”? It is to this question that I now turn.

8.4 Thinking with *mental* diagrams

8.4.1 Using mental images

Given the advantages of visual displays in aiding certain kinds of reasoning, it is very tempting to think that mental diagrams would do the same, especially since it feels like you are looking at a diagram when you imagine it. Indeed, many of the scholars who have studied the role of diagrams in reasoning have taken it for granted that their analysis applies to mental diagrams as well, so that visual thinking has come to mean thinking with the aid of visualized (mental) diagrams (Jamnek, 2001). There is no denying that in some ways mental images may help reasoning; the problem is to say in what ways they might help reasoning despite the fact that many of the features of visually augmented reasoning discussed in the previous section do not apply to images. For example, you cannot recognize new patterns in images (except for simple ones that you arguably “figure out” rather than perceive using the visual system); you do not have a special facility to detect such properties as region inclusion or intersection (as in Figure 8-3 or Figure 8-5) you cannot “see” properties in an image you did not independently know were there or detect the similarity of figures constructed as a result of drawing certain new lines, as in Figure 8-4; you cannot rely on being able to access several items at once to detect relational properties (such as collinearity and enclosure); and you could not construct a set of distinct cases, such as those in section 8.3.3 and 8.3.5, and use them as an extended memory (since the “internal” memory of your mental image is severely limited).

We saw (in chapter 1, and in various places in the last 3 chapters) that there is a great deal of evidence showing that both visual percepts and imagined pictures are very different from physical drawings. When we imagine carrying out certain operations on mental images (e.g., scanning them, or drawing a line on them) what we “see” happening in our mind’s eye is just what we believe would happen if we were looking at a scene and carried out the real operation, nothing more or less than that. As a result, we cannot rely on discovering something by observing what actually happens, as we might if we were drawing on a piece of paper. Our mental picture also does not have the benefit of being a rigid surface so it does not have the stability and invariance of properties that a physical picture would have when various operations are applied to them. For example unlike a physical diagram, a mental image does not automatically retain its rigid shape when it is transformed, say by rotating it or moving parts of it around or by folding it over, or adding new elements to it. This is because there is actually no inner drawing surface to give an image its rigidity and permanence and because “noticing” new visual patterns in an image is largely an illusion (see Chapter 7).

Just to remind you of the ephemeral quality of image properties, try to imagine a diagram in which you do not know in advance where the elements will fall. For example, imagine an arbitrary triangle and draw lines from each vertex to the midpoint of the opposite side. Do the three lines you draw this way cross at a single common point, or do they form a small triangle inside the original triangle (and is this so for any triangle whatsoever)? Imagine a triangle drawn between a pair of parallel horizontal lines (with its base on

the bottom parallel and its remaining vertex on the top parallel) and transform the triangle by sliding the top vertex along the line it is on until the triangle becomes highly skewed. (What happens to its area?) Now draw a vertical line from the top vertex to the bottom parallel and two other vertical lines from the bottom vertices of the triangle to the top parallel. How many triangles are there now, and are any of them identical? Imagine a string wrapped around two partially embedded nails, and held taught by a pencil (so the string makes a triangle). Now move the pencil around wherever it can go while keeping the string taught and let it draw a figure on the table: What does this figure look like? Or, to repeat an example I cited earlier, imagine a pair of identical parallelograms, one above the other, with corresponding vertices of the two parallelograms joined by vertical lines. Look at it carefully and note what it looks like. Now draw it and look at the drawing (and do the same with the other examples, draw them and see how they look compared with how they looked in your image). (Hinton, 1987) provides another example showing that images may lack properties that one naturally attributes to them. His example focuses on the concept of horizontal and vertical. Imagine a three-dimensional cube. Place a finger of one hand on one of the vertices and a finger of your other hand on the diagonally opposite vertex. Now hold the cube between these two fingers in such a way that the two vertices are directly above one another (and the solid is now being held with its diagonal vertical). Now without first thinking about it, count the remaining vertices of the figure as they appear in your image, and say where they are located relative to the two you are holding. Most people get the answer terribly wrong: they end up saying that there are four remaining vertices that lie on a plane, which of course leaves the cube with only 6 vertices whereas we know it has 8. Hinton argues that in rotating the imagined cube we must alter a description of it in order to conclude what it would look like in the new orientation, and in doing so we are deceived by thinking of the solid not as a cube but as a figure that is symmetrical about the new vertical axis.

We saw in chapter 7 that mental figures are not *visually* reinterpreted after we make changes or combine several figures, except in cases where the figures are sufficiently simple that one can figure out (by reasoning) what familiar shape they would look like. If we were to try to prove Pythagoras' Theorem by constructing the squares (as in Figure 8-4) in our mind, we would not be able to use our power of recognition to notice that there were 4 identical triangles, one in each corner – a recognition that is critical to determining how to proceed with proof. Although it is easy to explain some of these differences between pictures and mental images by saying that images are limited in their capacity. But while the capacity of mental imagery clearly is limited, the limitation is not one we can understand in terms of how many lines can be drawn, but in terms of how many conceptual units there are (as we saw in the examples of section 1.4.3). Moreover, such limitations are not compatible with the claims often made about the role of more complex images in reasoning, including a large range of experiments involving operations like scanning, rotation and changing the size of images.

The point here is the one that occupied the last 3 chapters of this book: namely, it is a mistake to think that when we are visualizing, there is something in our head that is being seen or is being *visually* interpreted. But if mental diagrams are so different from real diagrams, why then is it easier to do a problem such as the one we discussed earlier, illustrated in Figure 8-5, by imagining that figure in one's "mind's eye"? There is no doubt that it would be very difficult to do this extremely simple problem if one were barred from using a mental image, regardless of what form the image actually takes.⁷² Why should this be so if the image does not have essentially pictorial properties?

8.4.2 Using mental models

One might reply that while it may be a mistake to think of these diagram-like reasoning aids as actual figures, since the only properties that are used are the relative locations of items and their names, yet there may still be a representation of a spatial layout that is important to the reasoning. Such as spatial layout is

⁷² Notice that even here one needs a broader understanding of a "mental image" than the picture theory provides, since blind people can solve such problems without the experience of "seeing". Presumably other sensory modalities, or even unconscious spatial constructions of some sort could also be involved and therefore ought to be accommodated in our understanding of mental imagery.

all that is used in what (Johnson-Laird, 2001) calls “mental models” (see section 8.3.5). Although this avoids some of the problems of viewing the inner diagrams as things that are “seen”, it leaves many of the other serious problems intact. In particular in order for the inner mental models to take up some of the functions of external spatial models, we have to assume that mental models have properties of (appropriate) stability and (parallel) accessibility of relational information that are similar to those of external spatial models. As mentioned in connection with the discussion of what it could mean to say we “think in pictures,” much has to be going on off-stage and independent of the way the model appears when drawn on paper. For example when we set out the articles in the example discussed earlier in section 8.3.5 (involving the locations of a spoon, fork, plate and cup) certain assumptions were implicit: that when you place the cup in front of the knife the relative location of the spoon and plate remains unchanged, and that when told that the plate is to the right of the spoon, two possibilities had to be considered, as in layouts (6), in neither of which are the relative locations of the already placed items altered. Well, not quite. You will note that one possible way to place the plate to the right of the spoon is to intersperse the plate between the spoon and the knife (as was done in the left part of the pair of figures (6) in section 8.3.5). The fact that this did not alter the previously encoded relation between spoon and knife, and between the knife and the cup, is attributable to the user’s knowledge of both the formal relation “to the right of” (e.g., that it survives interpolation) and the pairwise cohesiveness of the knife-cup pair which were moved together because their relation was previously specified. Properties such as pairwise cohesiveness can be easily seen in a diagram where all that is required in order to place the plate to the right of the spoon is to move the plate-cup column over by one. This movement of a column is easy to understand in the diagram, but because rigidity of form (or constancy of pattern with rigid movement) is not a property of images, one would have separately compute what should happen to parts of a pattern when other parts are changed. This would depend on additional knowledge of when some things can change while other things remain unchanged (e.g., so-called frame axioms), so that the mental version of the model would not give the results that would be observed in the physical layout case without additional reasoning. “Mental models” like mental images, are assumed to have certain unstated properties because if they were drawn on paper, as they are when they are being explained, the properties would hold automatically by virtue of physical properties of the surface and properties of the visual system.

8.4.3 What happens during visualization?

If images (or mental models) have such serious inherent problems, why then do they appear to help – at least in some circumstances – in reasoning? Perhaps the reason does not lie in any of the intrinsic properties of images or models that are tacitly assumed. Perhaps it is because of the content of the image or model, and not its alleged spatial form. It is a general property of mental life that we tend to think different thoughts (thoughts with different contents) when we are presented with a problem in different ways (as Hayes & Simon, 1976, showed clearly). In fact a major step in problem-solving is formulating or representing the problem in an appropriate way (Herb Simon goes so far as to claim that “Solving a problem simply means representing it so as to make the solution transparent,” Simon, 1969). It appears that we think about different things (or at least we highlight different properties) when we *visualize* a situation than when we do not, and the perhaps the thoughts that arise under these conditions are helpful in solving certain kinds of problems, especially problems that concern spatial patterns. So part of the answer for why imagining a figure is sometimes helpful is surely that when we think in terms of spatial layouts we tend to think about different things and represent the problem in different ways from when we think in terms of abstract properties. Such thinking is rightly thought of as being more concrete because its contents (as opposed to its form) concern spatio-temporal and visual properties rather than abstract properties. When we think about a rectangle in the abstract we cannot readily understand the instruction to draw lines from the two bottom vertices to a point on the opposite side, because we may not have individuated these vertices: you can think “rectangle” without also thinking of each of the 4 vertices, but when you visualize a rectangle you do think of its 4 vertices.

My experience in using the example of Figure 8-5 in class is that the hardest part of solving the problem without using the blackboard is communicating the problem specifications. The way I am invariably forced

to do it is to ask students to imagine a rectangle whose vertices are labeled, starting from the bottom left corner and going clockwise, as A, B, C, and D and then drawing a line from A to any point on CD and from D to any point on AB. By conveying the problem in this way I ensured that the individual vertices will be distinct parts of the representation of the figure and I also provided a way to refer to them individually. This makes the task somewhat easier precisely because this way of describing the problem sets up thoughts about a particular rectangle and about particular individuated and labeled vertices and sides. Even then one usually cannot select the side labeled CD without going through the vertex labels in order. Thus it may be that imaging certain figures is helpful in solving problems because this way of thinking about the problem (by imagining that one is seeing the figure) focuses attention on individual elements and their relational properties. This way of looking at the role of imagined figures is neutral on the question of the nature and form of the representation of mental images, and indeed may help to reduce the temptation to reify an inner diagram with its implication that the visual system's involvement in the visualization process is that of observing the mental image.

But why should imagery lead to entertaining certain kinds of representational contents, such as those alluded to above? In Chapter 7 (section 7.4.2) I discussed ways in which representations underlying mental images might differ from other sorts of cognitive representations. The main points were that images are a more restricted form of representation because they are confined to representing individual instances rather than the more general situations that can be described using quantified statements: they do not represent the belief that all crows are black but only that crow #1 is black, crow #2 is black, crow #3 is black, and so on. They individuate elements of a situation and may represent parts of a scene by parts of the representation. They also tend to attribute properties to particular elements (as in, crow #1 is black). They do not contain quantifiers or negation, except by the addition of annotations that have to be interpreted by mechanisms outside the imagery system (by the sorts of mechanisms that interpret symbolic expressions). Thus such representations are more like a relational database or a restricted representational language, like Levesque's "vivid representation" (Levesque, 1986). Beyond such properties, which images do share with pictures (but also with relational databases), there are few pictorial properties that withstand careful scrutiny, including the widely believed spatial nature of images. While individuating elements could involve representing them in distinct physical locations, the locations and relations among locations are no more signifying than are locations of variables in a computer, or of the physical location of cells in a matrix data structure.

8.5 Imagery and imagination

One of the most interesting questions one might ask about mental imagery is how it serves as a vehicle for creative imagination, for there is no doubt that creativity often starts with imagining things that do not yet exist. Before considering this question, I want to point out a systematic ambiguity in discussions about imagination. There are two senses in which we can talk about imagining something. One is the sense in which a person might imagine *seeing* something (often referred to as "imaging" or as "visualizing"). The other is the sense in which a person simply considers a (counterfactual) situation in which something might be true. This is the difference between "imagining X" and "imagining *that X is the case*", or between imagining seeing X and considering the implications of X being the case (as in "what if X were true?"). Clearly, the latter is essential not only for creative invention, but also for mundane planning. In order to make a plan one needs to consider non-actual (or counterfactual or fictitious) situations; one must be able to think "If I did this then it would result in such-and-such," which entails considering (and therefore representing) some non-actual state of affairs. There is much that can be said about this subjunctive or imagining-that form of reasoning (see, e.g., Harper, Stalnaker & Pearce, 1981) but it clearly does not require generating a mental image; it does not require "seeing in the mind's eye". The other sense of imagining does require entertaining such a mental image since it in effect means "imagine what it would look like if you were to see...." some particular situation. What exactly it means, in terms of information processing mechanisms and operations, to imagine that you were seeing something is what this discussion of mental imagery has been about. What we know is that it does not mean that we have a picture of the situation displayed in our brain. We also have good reason to think it involves entertaining a symbolic representation

of some counterfactual situation (with or without an analogue representation of relevant magnitudes). Beyond that there is not much we can say about this process that would cast light on its role in creative visualization.

Yet the history of science abounds in examples of important discoveries being made when the scientist thinks about a problem visually (this idea is discussed very widely – see Shepard, 1978a, for a good summary of this point with extensive biographical citations). Scientists as illustrious as Albert Einstein reported that he thought in images. Libraries are full of books about the creativity of visual thinking. How do all these reports square with what I have been saying about the non-pictorial nature of imagery and especially of the non-pictorial nature of thinking and reasoning? Are these reports simply misled or romanticized? The simple answer is that what people are reporting does not constitute a theory of what goes on in the mind that is causally responsible for episodes of creative thinking. It is thus neutral on the question of whether thinking using mental images consists of examining pictorial entities in one's head. As I have said many times throughout this book, such reports describe what people are thinking *about*, not what they are thinking *with* and in any case they are not reports of causal processes underlying the experiences. For example, in the very widely cited case of Albert Einstein, what Einstein claimed was that (a) his thoughts were not expressed in words, at least not initially, (b) his discoveries were not made in a strictly logical manner, and (c) many of his ideas were developed by “thought experiments” in which, for example, he imagined himself traveling along the front of a beam of light at the speed of light. Interpreting this to mean that a “visual” mode of reasoning is more creative than other modes requires acceptance of a version of the dual code idea (i.e., what is not logical is not verbal and what is not verbal is pictorial). It also requires conflating two senses of “imagine” that I mentioned at the beginning of this section; a sense that means “consider what it would be like if x were true,” and a sense that means “imagine seeing x happen”. Evidence that scientists do not think “in words” or that they do not discover new theories by following (deductive) logic tells us nothing about the process that they do go through – nobody thinks “in words” nor do they make explicit use only of deductive logic in forming hypothesis. To say that they do it “by intuition” is to admit that we have no idea how the thoughts unfolded.

While admitting our current state of ignorance about such things as where creative ideas come from, it is worthwhile to keep in mind where the real mystery lies. It lies not in questions about the nature of mental images, but in questions about the nature of creative thought, and in particular in the question of where new ideas come from. Images, like language, are at most a vehicle for expressing ideas. They cannot explain their origins, much as it may be tempting to think that we simply “notice” something new or are “inspired” to have novel thoughts by observing our images unfold. The fact that a new idea may arrive accompanied by a particular image (e.g., Kekulé's dream of the snake swallowing its tail, which suggested the shape of the benzene molecule) is not the central fact; what is central is the idea which caused this image in the first place and we have not the lightest notion where that came from. Recalling, or calling to mind, is equally mysterious whether or not it is accompanied by the experience of a mental image. The source of our ideas is, as Kant put it (Kant, 1998), “... an art, hidden in the depths of the human soul, whose true modes of action we shall only with difficulty discover and unveil.” But that is no reason to substitute one mystery (how images are involved in creative insights) for another (where new thoughts come from).

Most writings about the role of imagery in creative problem solving and in psychotherapy typically do not, or at least do not need to, make assumptions about the form or structure of images, nor even whether thoughts and images are different in any way except for what they are about. The term “imagery” is used essentially synonymously with “imagination.” Clearly when we imagine or visualize a scene we are attending to different properties than we would if we were to, say, formulate a written description of it. The question of whether when we have the experience of “seeing in our mind's eye” we are thinking about different things, whether the subject or the meaning of our thoughts is different, is not in contention. It is obvious that when I think about a painting I am thinking of different things than when I think about mathematics. Even when the subject matters are similar, the difference between them may be the main point of differentiation between imagery-thoughts and non-imagery-thoughts. For example I can think about my office room with or without visualizing it. But when I visualize it, the subject matter of my thought includes the appearance of the room and some of the individual things in it. When I think about my office

room without visualizing it I have selected certain aspects of the room to be the subject of my thoughts. While I can think some thoughts about specific visual features, such as where the chair is located, without visualizing the room, the subject matter is still different. The thought may not contain explicit references to colors or sizes or shapes. But this difference is still a content difference and not a form difference. The same is true of other uses of mental images, say in problem solving, as we saw in the previous section. The difference between thinking about geometrical theorems with or without visualizing is largely that in the latter case I am actually thinking of the details of a *particular token* figure (a particular triangle or diagram). The question of whether this entails a different form of representation is not addressed by the mere fact that in one case I visualize something and in another I do not.

One of the reasons why imagery is widely thought to contain the secret of creative imagination lies in its apparent autonomy and freedom from conscious ratiocination; it often seems to us that we “see” new meanings in images or that new ideas are “suggested” to us in a quasi visual mode, and that this process follows a different logic, or perhaps no logic at all but some other intuitive principles.⁷³ The terminology of “seeing” is frequently used to indicate a new way of conceptualizing a problem or idea (as in “Now I see what you mean”). It has even been suggested that the process of *seeing as* hides the secret of the role of imagery in creative imagination. But as I argued earlier (and in Pylyshyn, 1999) *seeing as* is the clearest example of an aspect of visual perception that is not constitutive of and unique to vision. Unlike the processes of early vision, *seeing as* occurs in the stage of visual perception that is shared with cognition generally. *Seeing as* involves not only seeing, but also reasoning, recalling and recognizing. It is the part of the visual process where belief fixation occurs, as opposed to the process in which the appearance of a scene as a set of three-dimensional surfaces is computed, and is consequently where vision crosses over to memory, recognition, inference, decision making and problem solving. It is not the case, as many writers have assumed, that the sorts of semantically-coherent processes that operate over beliefs and that lead to new beliefs, are capable of only rigid logical reasoning. While these processes do respect the meaning of representations and therefore lead to thoughts whose content has some connection to the content of other thoughts that trigger them, they need not be confined to logical or rational processes; semantic coherence is also true of creative innovation. The difference is that while we know something about rational reasoning (thanks to work on the foundations of logic over the past century) we know next to nothing about non-demonstrative, abductive, or common-sense reasoning and even less about creative reasoning. However none of this ignorance is aided by talk of the role of the mind’s eye in creativity since that just substitutes one mystery for another.

Having said this, it nonetheless behooves us to consider ways in which the imagery system might take part in creative reasoning and problem solving, for it is clear that there is something special about what we can do when we are imagining that is different from what we can do when we are not.

8.5.1 How does creativity connect with imagery?

One idea that plays a role in virtually every theory of creative thinking is the notion that at some stage thinking makes a non-logical leap; reasoning happens, as has sometimes been said, “outside the box”. Of course not anything outside the box is creative reasoning, some of it is just crazy. The creative step must not merely be a non sequitur, but it must be related somehow to the topic at hand. So anything that can encourage nonlogical, yet content-related, progression of thoughts could conceivably serve as a stage or a catalyst for creative thinking. Indeed several theories explicitly posit stages in which representations are altered in random ways and many methods that teach creative thinking using imagery do encourage people to come up with nonlogical connections, to create associations based on similarities and to follow leads based on ideas suggested by the images. Random perturbations by themselves serve no function (as they say in the computer field, *Garbage In, Garbage Out*). But randomness in conjunction with selectivity can,

⁷³ The notion that ideas interact according to special mental principles is close to the British Empiricist notion of “mental chemistry,” according to which the formation of concepts and the flow of thought is governed by principles such as temporal and spatial contiguity, repetition, similarity, and vividness, which were believed to favor the formation of associations.

at least in principal, lead to some creative leaps. Yet this too is not enough. The proverbial thousand monkeys at typewriters will never produce Shakespearian prose, even if the probability is actually finite. What is needed for a genuine creative product (other than the skill to produce it) is some content-restricted thought transitions that are non-deductive, in the sense that they are not like valid proofs, but are more like abductive conjectures. People have looked to imagery as a mechanism that might allow transitions that are nonlogical. For example, it has been suggested that when we examine a drawing or sketch that we have made based on ideas that are relevant to the problem at hand, we can “notice” consequences that we might not be able to infer explicitly, or we might be reminded of something by virtue of its similarity to the object depicted in the drawing, or we might use the drawing as a metaphor for some abstract concept with which we are struggling, and so on.

Despite the caveats I have offered concerning the significant differences between drawings and mental images, it could still be the case that the mere fact that one is visualizing (whatever that actually means in terms of information processes) brings to the fore certain properties of the object of our thoughts that are related to shape and appearance. After all, whatever else happens when we visualize, it is a matter of definition that we consider the appearance of the objects we visualize. So even though there need be no difference in the form of the information in thought and vision, the difference in content (in what we think about or what we emphasize) when we visualize could mean that different principles come into play in determining what one thinks of next. For example, thinking about the shape of particular figures may remind one of other figures that are similar in shape, so it may be that the “reminders” run along a shape-similarity dimension rather than some other dimension that would be more salient when the subject of the thoughts is something other than appearances. This emphasis on shape and shape-related relationships may even carry with it some of the same characteristics as those we observe when we perceive actual diagrams. So, for example, one can think about sets of things that have certain properties and one can think about how having certain properties entails having other properties, yet the reasoning process may be much easier if we think, instead, of the properties of intersection of circles in Venn diagrams *even if the mental representations do not themselves have circles, areas, overlapping regions* and so on. Just thinking about these properties in whatever form we think of them (e.g., in a symbolic language of thought) can still give us some of the benefit we would have if we had actual visible Venn diagrams. This can be true as long as it is easier (for whatever reason) to think about relations among regions, intersections between regions, and other properties of the same formal type.

There may be many quite different bases for the view that using mental images might enhance creativity. One is that it helps you to concentrate on certain aspects of a problem, such as its spatial or pattern aspect. Whether you draw a diagram or just think about it, your attention is directed to spatial patterns. Such patterns may be relevant for their own sake or they may have a metaphorical or symbolic connection with some other domain (as with Venn diagrams). Another basis for the idea that imagery may enhance creativity is that it allows principles other than logical inference (e.g., “reminders”) to take part in the process by which thoughts unfold.

Roger Shepard (Shepard, 1978a) has given a great deal of thought to the question of why images should be effective in creative thought and invention. He lists four general properties of imagery that make them especially suitable for creative thought. These are (pp 156): “their private and therefore not socially, conventionally, or institutionally controlled nature; their richly concrete and isomorphic structure; their engagement of highly developed, innate mechanisms of spatial intuition; and their direct emotional impact.” These are perfectly reasonable speculations, with varying plausibility. The first general property (imagery is more private) rests on the dual code assumption since there is no reason why a pictorial form of representation is any more immune from external control than the form that I have discussed in this book (i.e., a conceptual system or “language of thought”). The second property (isomorphic structure) relies on a theory of imagery that suffers from either unconstrained interpretation or lack of empirical support. As we saw in section 6.3.2.3, the sort of isomorphism that Shepard has in mind (what he elsewhere calls “second order isomorphism”) is a requirement for any adequate representation and leaves open the crucial question of whether this arises from intrinsic properties of the representation or from inferences based on tacit knowledge. Consequently, while the claim that images have a concrete and isomorphic structure is a

reasonable one, it does not favor one theory of image representation over another, although it does suggest that perhaps thinking in terms of concrete (token) instances may be an effective way to induce creative leaps. The third property (images engage mechanisms of spatial intuition) is also reasonable, and in fact is in accord with proposals I made earlier in sections 7.2 and 7.3 where I discuss reasons why mental images appear to have “spatial” properties. There is no doubt that our spatial sense is extremely central in how we cognize the world and may be particularly relevant when we think about spatial patterns, shapes, and the operation of physical mechanisms. But once again, the impression that we “see” things is misleading. What we do, according to the analysis presented in Chapter 7, is think of individual things as located in a space that we are currently perceiving, visually or proprioceptively. As I argued in section 7.3, we may use the real physical space that we perceive with one or another sense as a receptacle into which we can project spatial patterns that we are thinking about, and in this way make use of the “highly developed, innate mechanisms of spatial intuition” that Shepard speaks of. In fact, as mentioned in section 7.3, we can even use this spatial sense in order to individuate and keep track of abstract ideas.

The last property that Shepard proposed as a basis for the superiority of mental images over words in promoting creative thought, is their “direct emotional impact.” Once again this is a reasonable proposal which does not favor one theory of the nature of mental images over another. It is true that if we think the sentence “I am about to be hit by a falling brick” we are not nearly as moved to action, or to emotion, as we are if we imagine that a brick is falling down on us. While there has not been a great deal of emphasis placed on this aspect of mental imagery, it is surely very important. On a personal level, this property of images to create states of fear, anxiety or arousal, is a property that had been most difficult for me personally to come to terms with in reorienting my own thinking concerning the nature of mental images. Dealing with this puzzling property requires continually reminding oneself that the crucial parallel between seeing and emotional states, on the one hand, and thinking and emotional states on the other, must both be mediated by mental representations and that the form (and content) of those representations may well be the same in both cases, so the parallel is not surprising. Moreover, as we saw in Chapter 1, there is good reason to believe that in neither case is this representation pictorial (nor is it verbal). Mental representations are powerful forces in our lives and representations of particular things and events are more powerful than representations of general principles.

8.5.1.1 Enhancing creative thinking

Creativity is much prized in our culture (though perhaps not quite as much as high achievement). It is also much misunderstood (for example it is associated with being a misfit, with nearness to insanity and so on). Measures of intelligence and of creativity, despite their many shortcomings, have generally shown the two to be highly related. This is not surprising since it is hard to be creative if you don’t understand the problem or are unable to reason about it well. However since creativity is especially prized in certain fields (e.g., science and art), people have tried to find specific (personality, style) factors that distinguish them. Such factors are bound to be there since we do have at least some vague idea of what distinguishes creativity from mere ability. Some of the studies have led to interesting findings and have connected creativity to nonstandard ways of thinking or nonstandard values (e.g., a playful attitude towards problems and a high value placed on finding and formulating problems, see Getzels & Jackson, 1962). In any case what we consider to be creative solutions to a problem often require that the problem-solver generate a space of options that go beyond the expected or the obvious. For this reason many creativity-enhancing techniques encourage free association, exploration of unusual similarities and relationships among elements of the problem, and other tricks to help bring to the fore aspects that might not readily come to mind in connection with the problem at hand – all in the interest of temporarily subverting habitual modes of thought and reasoning.

An example of the use of mental imagery to generate associations and to trigger alternative ideas in this way is the game that (Finke, 1990) used to study the enhancement of creativity through mental imagery. This game asks people to make a sketch of what they think of when they think about a certain problem (or just to sketch some object involved in that problem) and then to modify it in certain ways or just think of what it reminds you of. The game relies in the fact that the manipulation of shapes and the recognition of

similarity of shape and can remind one of things that are not connected to the problem in a logical goal-directed way, and thereby influence the sequence of thoughts one goes through in coming up with a novel idea. There are many examples of the use of this and other techniques relying on mental imagery to enhance creativity – in fact the World Wide Web is filled with “creativity resources” consisting of everything from computer programs to actual physical devices, all designed to discourage one’s normal problem-solving habits.

Much of the advice for enhancing creative problem solving is focused quite specifically on encouraging nonstandard ways of thinking about a problem by emphasizing the association of ideas over more direct ways of working on a problem, such as deduction and search (or means-ends analysis). In fact some of the tools that have been claimed to enhance creativity are just tools for inhibiting the usual habits of problem solving from controlling the process. (Gardner, 1982, p27) describes what he calls “whimsical” devices for breaking away from “vertical thinking” into “lateral thinking”. For example, there is a device called the “Think Tank” which is a rotating drum containing 13,000 tiny plastic chips, each with a word printed on it. When the drum is rotated, different words come into view and the user is invited to free associate to each word or phrase. Related tools are being sold today that run on computers and produce graphic pictures that allow you to connect ideas (e.g., the “Mind Mapper”). Some years ago there was even a special room, called the Imaginarium (McKim, 1978), for training people to think creatively by leading them through a sequence from relaxation, through imagining the superposition and transformation of images (done with the help of slides and sounds), through a series of fantasies involving metaphors, to Zen-like attention to the here-and-now, coupled with physical exercises. What all these ideas and methods have in common is this: They tend to encourage you to do things in a different way from how you would normally do them (and perhaps even to feel different about what you are doing).

Of course not any different way is a good way, but it may well be a useful starting heuristic. And so it is with many uses of imagery. Associating to images may be different from associating to words, but association is no way to enhance creativity. Or is it? After looking at a wide range of claims about how imagery enhances creativity it seems to me to be a mixed bag: it includes everything from advice on the use of graphics and other tools to the equivalent of giving a thousand monkeys graphics software instead of typewriters. It is safe to say that in the present state of our understanding of both creativity and mental imagery, this heterogeneous collection of talismans tells us little about the nature of creativity and even if it did enhance one’s creativity that would be no more informative than the discovery of the power of placebos to alter one’s somatic complaints. They may work, but they tell us nothing about the underlying mechanisms.

REFERENCES

- Abernethy, B. (1991). Visual search strategies and decision-making in sport. Special issue: Information processing and decision making in sport. *International Journal of Sport Psychology*, 22(3-4), 189-210.
- Abernethy, B., Neil, R. J., & Koning, P. (1994). Visual-perceptual and cognitive differences between expert, intermediate and novice snooker players. *Applied Cognitive Psychology*, 8(3), 185-211.
- Acton, B. (1993). *A Network Model of Visual Indexing and Attention*. Unpublished MSc, University of Western Ontario, London, Canada.
- Aglioti, S., DeSouza, J. F. X., & Goodale, M. A. (1995). Size-contrast illusions deceive the eye but not the hand. *Current Biology*, 5(6), 679-685.
- Allwein, G., & Barwise, J. (Eds.). (1996). *Logical reasoning with diagrams*. New York: Oxford University Press.
- Anderson, B., & Johnson, W. (1966). Two Kinds of Set in Problem Solving. *Psychological Reports*, 19(3), 851-858.
- Anderson, J. R. (1978). Argument Concerning Representations for Mental Imagery. *Psychological Review*, 85, 249-277.
- Anderson, R. A., Snyder, L. H., Bradley, D. C., & Xing, J. (1997). Multimodal representation of space in the posterior parietal cortex and its use in planning movements. *Annual Review of Neuroscience*, 29, 303-330.
- Annan, V., & Pylyshyn, Z. W. (2002). ***Can indexes be voluntarily assigned in multiple object tracking?*** Paper presented at the Vision Sciences 2002, Sarasota, FL.
- Ashby, F. G., Prinzmetal, W., Ivry, R., & Maddox, W. T. (1996). A formal theory of feature binding in object perception. *Psychological Review*, 103(1), 165-192.
- Attneave, F. (1954). Some informational aspects of visual perception. *Psychological Review*, 61, 183-193.
- Attneave, F., & Farrar, P. (1977). The visual world behind the head. *American Journal of Psychology*, 90(4), 549-563.
- Attneave, F., & Pierce, C. R. (1978). Accuracy of extrapolating a pointer into perceived and imagined space. *American Journal of Psychology*, 91(3), 371-387.
- Avant, L. L. (1965). Vision in the ganzfeld. *Psychological Bulletin*, 64, 246-258.
- Bachmann, T. (1989). Microgenesis as traced by the transient paired-forms paradigm. *Acta Psychologica*, 70, 3-17.
- Backus, J. (1978). Can Programming Be Liberated from the von Neumann Style? A Functional Style and Its Algebra of Programs. *Communications of the Association for Computing Machinery*, 21, 613-641.
- Ballard, D. H., Hayhoe, M. M., Pook, P. K., & Rao, R. P. N. (1997). Deictic codes for the embodiment of cognition. *Behavioral and Brain Sciences*, 20(4), 723-767.
- Banks, W. P. (1981). Assessing relations between imagery and perception. *Journal of Experimental Psychology: Human Perception and Performance*, 7, 844-847.
- Barolo, E., Masini, R., & Antonietti, A. (1990). Mental rotation of solid objects and problem-solving in sighted and blind subjects. *Journal of Mental Imagery*, 14(3-4), 65-74.
- Baron-Cohen, S., Harrison, J., Goldstein, L. H., & Wyke, M. (1993). Coloured speech perception: Is synaesthesia what happens when modularity breaks down? *Perception*, 22(4), 419-426.
- Baron-Cohen, S., & Harrison, J. E. (Eds.). (1997). *Synaesthesia: Classic and Contemporary readings*. Cambridge, MA: Blackwell.
- Barsalou, L. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences*, 22(4), 577-660.
- Bartolomeo, P., Bachoud-levi, A. C., & Denes, G. (1997). Preserved imagery for colours in a patient with cerebral achromatopsia. *Cortex*, 33(2), 369-378.
- Bartolomeo, P., & Chokron, S. (2002). Orienting of attention in left unilateral neglect. *Neuroscience and Biobehavioral Reviews*, 26(2), 217-234.
- Barwise, J., & Etchemendy, J. (1990). Information, inferences, and inference. In R. Cooper & K. Mukai & J. Perry (Eds.), *Situation theory and its applications, I*. Chicago, IL: University of Chicago Press.
- Baylis, G. C. (1994). Visual attention and objects: Two-object cost with equal convexity. *Journal of Experimental Psychology: Human Perception and Performance*, 20, 208-212.
- Baylis, G. C., & Driver, J. (1993). Visual attention and objects: Evidence for hierarchical coding of location. *Journal of Experimental Psychology: Human Perception and Performance*, 19, 451-470.
- Behrmann, M. (2000). The mind's eye mapped onto the brain's matter. *Current Directions in Psychological Science*, 9(2), 50 - 54.

- Behrmann, M., Moscovitch, M., & Winocur, G. (1994). Intact visual imagery and impaired visual perception in a patient with visual agnosia. *Journal of Experimental Psychology: Human Perception and Performance*, 20(5), 1068-1087.
- Behrmann, M., & Tipper, S. (1994). Object-based visual attention: Evidence from unilateral neglect. In C. Umiltà & M. Moscovitch (Eds.), *Attention and Performance 15: Conscious and unconscious processing and cognitive functioning* (Vol. 19, pp. 351-375). Cambridge, MA: MIT Press.
- Behrmann, M., & Tipper, S. (1999a). Attention accesses multiple reference frames: Evidence from unilateral neglect. *Journal of Experimental Psychology: Human Perception and Performance*, 25, 83-101.
- Behrmann, M., & Tipper, S. P. (1999b). Attention accesses multiple reference frames: Evidence from visual neglect. *Journal of Experimental Psychology: Human Perception & Performance*, 25(1), 83-101.
- Behrmann, M., Winocur, G., & Moscovitch, M. (1992). Dissociation between mental imagery and object recognition in a brain-damaged patient. *Nature*, 359(6396), 636-637.
- Bennett, B., Hoffman, D., & Prakash, K. (1989). *Observer Mechanics: A formal theory of perception*. New York: Academic Press.
- Berger, G. H., & Gaunitz, S. C. (1977). Self-rated imagery and vividness of task pictures in relation to visual memory. *Br J Psychol*, 68(3), 283-288.
- Bernbaum, K., & Chung, C. S. (1981). Müller-Lyer illusion induced by imagination. *Journal of Mental Imagery*, 5(1), 125-128.
- Beschin, N., Cocchini, G., Della Sala, S., & Logie, R. H. (1997). What the eyes perceive, the brain ignores: a case of pure unilateral representational neglect. *Cortex*, 33(1), 3-26.
- Biederman, I. (1987). Recognition-by-components: A theory of human image interpretation. *Psychological Review*, 94, 115-148.
- Biederman, I. (1995). Visual object recognition. In S. M. Kosslyn & D. N. Osherson (Eds.), *Visual Cognition* (second ed.). Cambridge, MA: MIT Press.
- Biederman, I., & Bar, M. (1999). One-shot viewpoint invariance in matching novel objects. *Vision Research*, 39(17), 2885-2899.
- Biederman, I., & Cooper, E. E. (1992). Size invariance in visual object priming. *JEP:HPP*, 18, 121-133.
- Biederman, I., & Gerhardstein, P. C. (1993). Recognizing depth-rotated objects: Evidence and conditions for three-dimensional viewpoint invariance. *Journal of Experimental Psychology: Human Perception & Performance*, 19(6), 1162-1182.
- Biederman, I., & Shiffrar, M. S. (1987). Sexing day-old chicks: A case study and expert systems analysis of a difficult perceptual-learning task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 13(4), 640-645.
- Binford, T. O. (1971, December). *Visual perception by computer*. Paper presented at the IEEE Systems Science and Cybernetics Conference, Miami.
- Bisiach, E., & Luzzatti, C. (1978). Unilateral neglect of representational space. *Cortex*, 14(1), 129-133.
- Bisiach, E., Ricci, R., Lualdi, M., & Colombo, M. R. (1998). Perceptual and response bias in unilateral neglect: Two modified versions of the Milner Landmark task. *Brain & Cognition*, 37(3), 369-386.
- Blackmore, S. J., Brelstaff, G., Nelson, K., & Troscianko, T. (1995). Is the richness of the visual world an illusion? Transsaccadic memory for complex scenes. *Perception*, 24(9), 1075-1081.
- Blanchard, R. (1975). The effect of S- on observing behavior. *Learning & Motivation*, 6(1) Feb 1975, US, <http://www>.
- Blaser, E., Pylyshyn, Z. W., & Holcombe, A. (2000a). With two objects at one location, attention is "object-based" (abstract). *Investigative Ophthalmology and Vision Research*.
- Blaser, E., Pylyshyn, Z. W., & Holcombe, A. O. (2000b). Tracking an object through feature-space. *Nature*, 408(Nov 9), 196-199.
- Block, N. (1981). Introduction: What is the issue? In N. Block (Ed.), *Imagery* (pp. 1-16). Cambridge, MA: MIT Press.
- Block, N. (1995). On a Confusion about a Function of Consciousness. *Behavioral and Brain Sciences*, 18, 227-247.
- Block, N. (2001). Is the content of experience the same as the content of thought? In D. Emmanuel (Ed.), *Language, Brain, and Cognitive Development: Essays in honor of Jacques Mehler*. Cambridge, MA: MIT Press/Bradford Books.
- Block, N., Flanagan, O., & Guzeldere, G. (Eds.). (1997). *The Nature of Consciousness: Philosophical Debates*. Cambridge, MA: MIT Press.

- Bolles, R. C. (1969). The role of eye movements in the Muller-Lyer illusion. *Perception & Psychophysics*, 6(3), 175-176.
- Bower, G. H., & Glass, A. L. (1976). Structural units and the reintegrative power of picture fragments. *Journal of Experimental Psychology: Human Learning and Memory*, 2, 456-466.
- Brawn, P. T., & Snowden, R. J. (2000). Attention to overlapping objects: Detection and discrimination of luminance changes. *Journal of Experimental Psychology: Human perception and Performance*, 26(1), 342-358.
- Bregman, A. (1990). *Auditory scene analysis: The perceptual organization of sound*. Cambridge, MA: MIT Press.
- Bridgeman, B. (1992). Conscious vs. unconscious processes: The case of vision. *Theoretical Psychology*, 2, 73-88.
- Bridgeman, B. (1995). Dissociation between visual processing modes. In M. A. Arbib (Ed.), *The Handbook of Brain Theory and Neural Networks*. Cambridge, MA: MIT Press.
- Briggell, M., Uhlarik, J., & Goldhorn, P. (1977). Contextual influence on judgments of linear extent. *Journal of Experimental Psychology: Human Perception & Performance*, 3(1), 105-118.
- Broadbent, D. E. (1958). *Perception and Communication*. London: Pergamon Press.
- Broerse, J., & Crassini, B. (1981). Misinterpretations of imagery-induced McCollough effects: A reply to Finke. *Perception and Psychophysics*, 30, 96-98.
- Broerse, J., & Crassini, B. (1984). Investigations of perception and imagery using CAEs: The role of experimental design and psychophysical method. *Perception & Psychophysics*, 35(2), 155-164.
- Brooks, L. R. (1968). Spatial and verbal components of the act of recall. *Canadian Journal of Psychology*, 22(5), 349-368.
- Brooks, R. A. (1991). Intelligence without representation. *Artificial Intelligence*, 47, 139-159.
- Brown, C. M. (1984). Computer vision and natural constraints. *Science*, 224(4655), 1299-1305.
- Bruner, J., & Postman, L. (1949). On the perception of incongruity: a paradigm. *Journal of Personality*, 18, 206-223.
- Bruner, J. S. (1957). On perceptual readiness. *Psychological Review*, 64, 123-152.
- Bruner, J. S., & Minturn, A. L. (1955). Perceptual identification and perceptual organization. *Journal of General Psychology*, 53, 21-28.
- Bruner, J. S., & Potter, M. C. (1964). Interference in visual recognition. *Science*, 144, 424-425.
- Burkell, J., & Pylyshyn, Z. W. (1997). Searching through subsets: A test of the visual indexing hypothesis. *Spatial Vision*, 11(2), 225-258.
- Cai, R. H., & Cavanagh, P. (2002). *Motion interpolation of a unique feature into gaps and blind spots*. Paper presented at the Vision Sciences 2002, Sarasota, FL.
- Calis, G. J., Sterenborg, J., & Maarse, F. (1984). Initial microgenetic steps in single-glance face recognition. *Acta Psychologica*, 55(3), 215-230.
- Canon, L. K. (1970). Intermodality inconsistency of input and directed attention as determinants of the nature of adaptation. *Journal of Experimental Psychology*, 84(1), 141-147.
- Canon, L. K. (1971). Directed attention and maladaptive "adaptation" to displacement of the visual field. *Journal of Experimental Psychology*, 88(3), 403-408.
- Carlson-Radvansky, L. A. (1999). Memory for relational information across eye movements. *Perception & Psychophysics*, 61(5), 919-934.
- Carpenter, P. A., & Eisenberg, P. (1978). Mental rotation and the frame of reference in blind and sighted individuals. *Perception & Psychophysics*, 23(2), 117-124.
- Casey, E. (1976). *Imagining: A phenomenological Study*. Bloomington, IN: Indiana University Press.
- Castiello, U., & Umiltá, C. (1992). Orienting attention in volleyball players. *International Journal of Sport Psychology*, 23(4), 301-310.
- Cavanagh, P. (1988). Pathways in early vision. In Z. W. Pylyshyn (Ed.), *Computational Processes in Human Vision: An interdisciplinary perspective* (pp. 239-262). Norwood, NJ: Ablex Publishing.
- Cavanagh, P. (1999). Attention: Exporting vision to the mind. In C. Taddei-Ferretti & C. Musio (Eds.), *Neuronal Basis and Psychological Aspects of Consciousness* (pp. 129-143). Singapore: World Scientific.
- Chakravarty, I. (1979). A generalized line and junction labeling scheme with applications to scene analysis. *IEEE Transactions, PAMI*, 202-205.
- Chalmers, D. J. (1996). *The conscious mind: In search of a fundamental theory*. New York, NY, USA: Oxford University Press.

- Chambers, D., & Reisberg, D. (1985). Can mental images be ambiguous? *Journal of Experimental psychology*, *11*, 317-328.
- Chara, P. J., & Hamm, D. A. (1989). An inquiry into the construct validity of the Vividness of Visual Imagery Questionnaire. *Perceptual & Motor Skills*, *69*(1), 127-136.
- Charlot, V., Tzourio, N., Zilbovicius, M., Mazoyer, B., & Denis, M. (1992). Different mental imagery abilities result in different regional cerebral blood flow activation patterns during cognitive tasks. *Neuropsychologia*, *30*(6), 565-580.
- Chase, W. G., & Simon, H. A. (1973). Perception in chess. *Cognitive Psychology*, *5*, 55-81.
- Chastain, G. (1995). Location coding with letters versus unfamiliar, familiar and labeled letter-like forms. *Canadian Journal of Experimental Psychology*, *49*(1), 95-112.
- Chatterjee, A., & Southwood, M. H. (1995). Cortical blindness and visual imagery. *Neurology*, *45*(12), 2189-2195.
- Cheng, K. (1986). A purely geometric module in the rat's spatial representation. *Cognition*, *23*, 149-178.
- Cherry, C. (1957). *On Human Communication* (Second ed.). Cambridge, MA: MIT Press.
- Chomsky, N. (1957). Review of B. F. Skinner's Verbal Behavior. In J. A. Fodor & J. J. Katz (Eds.), *The Structure of Language*. Englewood Cliffs: Prentice-Hall.
- Chomsky, N. (1976). *Reflections on Language*. New York: Fontana.
- Churchland, P. M. (1988). Perceptual plasticity and theoretical neutrality: A reply to Jerry Fodor. *Philosophy of Science*, *55*, 167-187.
- Clark, E. V. (1973). Nonlinguistic strategies and the acquisition of word meanings. *Cognition*, *2*, 161-182.
- Clark, H. H. (1969). Linguistic processes in deductive reasoning. *Psychological Review*, *76*(4), 387-404.
- Clowes, M. B. (1971). On Seeing Things. *Artificial Intelligence*, *2*, 79-116.
- Cocude, M., Mellet, E., & Denis, M. (1999). Visual and mental exploration of visuo-spatial configurations: behavioral and neuroimaging approaches. *Psychol Res*, *62*(2-3), 93-106.
- Cohen, M. S., Kosslyn, S. M., Breiter, H. C., DiGirolamo, G. J., Thompson, W. L., Anderson, A. K., Bookheimer, S. Y., Rosen, B. R., & Belliveau, J. W. (1996). Changes in cortical activity during mental rotation: A mapping study using functional MRI. *Brain*, *119*.
- Coren, S. (1986). An efferent component in the visual perception of direction and extent. *Psychological Review*, *93*(4), 391-410.
- Coren, S., & Porac, C. (1983). The creation and reversal of the Mueller-Lyer illusion through attentional manipulation. *Perception*, *12*(1), 49-54.
- Cornoldi, C., Bertucelli, B., Rocchi, P., & Sbrana, B. (1993). Processing capacity limitations in pictorial and spatial representations in the totally congenitally blind. *Cortex*, *29*(4), 675-689.
- Cornoldi, C., Calore, D., & Pra-Baldi, A. (1979). Imagery ratings and recall in congenitally blind subjects. *Perceptual & Motor Skills*, *48*(2), 627-639.
- Coslett, H. B. (1997). Neglect in vision and visual imagery: a double dissociation. *Brain*, *120*, 1163-1171.
- Coslett, H. B., & Saffran, E. (1991). Simultanagnosia: To see but not two see. *Brain*, *113*(1523-1545).
- Craig, E. M. (1973). Role of mental imagery in free recall of deaf, blind, and normal subjects. *Journal of Experimental Psychology*, *97*(2), 249-253.
- Crick, F., & Koch, C. (1995). Are we aware of neural activity in primary visual cortex? *Nature*, *375*(11), 121-123.
- Currie, C. B., McConkie, G. W., & Carlson-Radvansky, L. A. (2000). The role of the saccade target object in the perception of a visually stable world. *Perception and Psychophysics*, *62*, 673-683.
- Currie, G. (1995). Visual imagery as the simulation of vision. *Mind & Language*, *10*(1-2), 25-44.
- Cytowic, R. E. (1989). *Synaesthesia: A union of the senses*. New York, NY: Springer Verlag.
- Cytowic, R. E. (1993). *The Man Who Tasted Shapes*. New York, NY: Putnam.
- Dai, H., Scharf, B., & Buss, S. (1991). Effective attenuation of signals in noise under focused attention. *Journal of the Acoustical Society of America*, *89*(6), 2837-2842.
- Dalla Barba, G., Rosenthal, V., & Visetti, Y. -V. (2002). The nature of mental imagery: How "null" is the null hypothesis? *Behavioral and Brain Sciences*, *25*(2), xxx-xxx.
- Dalman, J. E., Verhagen, W. I. M., & Huygen, P. L. M. (1997). Cortical blindness. *Clinical Neurology & Neurosurgery*(Dec), 282-286.
- Dauterman, W. L. (1973). A study of imagery in the sighted and the blind. *American Foundation for the Blind, Research Bulletin*, 95-167.
- David, Driver, Pavani, & Shepherd. (in press). Reappraising the apparent costs of attending to two separate visual objects. *Vision*.

- Davies, T. N., & Spencer, J. (1977). An explanation for the Mueller-Lyer illusion. *Perceptual & Motor Skills*, 45(1), 219-224.
- Dawson, M., & Pylyshyn, Z. W. (1988). Natural constraints in apparent motion. In Z. W. Pylyshyn (Ed.), *Computational Processes in Human Vision: An interdisciplinary perspective* (pp. 99-120). Stamford, CT: Ablex Publishing.
- De Soto, C. B., London, M., & Handel, S. (1965). Social reasoning and spatial paralogic. *Journal of Personality & Social Psychology*, 2(4), 513-521.
- De Vreese, L. P. (1991). Two systems for colour-naming defects: verbal disconnection vs colour imagery disorder. *Neuropsychologia*, 29(1), 1-18.
- Dehaene, S. (1995). Electrophysiological evidence for category-specific word processing in the normal human brain. *Neuroreport: an International Journal for the Rapid Communication of Research in Neuroscience*, 6(16), 2153-2157.
- Dehaene, S., & Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: Basic evidence and a workspace framework. *Cognition*, 79(1-2), 1-37.
- DeLucia, P. R., & Liddell, G. W. (1998). Cognitive motion extrapolation and cognitive clocking in prediction motion tasks. *Journal of Experimental Psychology: Human Perception & Performance*, 24(3), 901-914.
- Démonet, J.-F., Wise, R., & Frackowiak, R. S. J. (1993). Language functions explored in normal subjects by positron emission tomography: A critical review. *Human Brain Mapping*, 1, 39-47.
- Denis, M., & Kosslyn, S. M. (1999). Scanning visual mental images: A window on the mind. *Cahiers de Psychologie Cognitive / Current Psychology of Cognition*, 18(4), 409-465.
- Dennett, D. C. (1991). *Consciousness Explained*. Boston: Little, Brown & Company.
- Dennett, D. C., & Kinsbourne, M. (1992). Time and the observer: The where and when of consciousness in the brain. *Behavioral & Brain Sciences*, 15(2), 183-247.
- DeSchepper, B., & Treisman, A. (1996). Visual memory for novel shapes: Implicit coding without attention. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 22(1), 27-47.
- Desimone, R. (1996). Neural mechanisms for visual memory and their role in attention. *Proceedings of the National Academy of Science, USA*, 93(24), 13494-13497.
- D'Esposito, M., Detre, J. A., Aguirre, G. K., Stallcup, M., Alsop, D. C., Tippet, L. J., & Farah, M. J. (1997). A functional MRI study of mental image generation. *Neuropsychologia*, 35(5), 725-730.
- Dodds, A. G. (1983). Mental rotation and visual imagery. *Journal of Visual Impairment & Blindness*, 77(1), 16-18.
- Driver, J. (1998). The neuropsychology of spatial attention. In H. Pashler (Ed.), *Attention* (pp. 297 - 340): Psychological Press.
- Driver, J., Baylis, G., Goodrich, S., & Rafal, R. D. (1994). Axis-based neglect of visual shapes. *Neuropsychologia*, 32, 1353-1365.
- Driver, J., & Halligan, P. (1991). Can visual neglect operate in object-centered coordinates? An affirmative single case study. *Cognitive Neuropsychology*, 8, 475-494.
- Driver, J., & Vuilleumier, P. (2001). Perceptual awareness and its loss in unilateral neglect and extinction. *Cognition*, 79(1-2), 39-88.
- Duncan, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology: General*, 113(4), 501-517.
- Duncan, J. (1993). Coordination of what and where in visual attention. *Perception*, 22(11), 1261-1270.
- Dunham, W. (1994). *The mathematical universe*. New York: John Wiley & Sons.
- Easterbrook, J. A. (1959). The effect of emotion on cue utilization and the organization of behavior. *Psychological Review*, 66, 183-201.
- Easton, R. D., & Bentzen, B. L. (1987). Memory for verbally presented routes: A comparison of strategies used by blind and sighted people. *Journal of Visual Impairment & Blindness*, 81(3), 100-105.
- Egly, R., Driver, J., & Rafal, R. D. (1994). Shifting visual attention between objects and locations: Evidence from normal and parietal lesion subjects. *Journal of Experimental Psychology: General*, 123(2), 161-177.
- Epstein, W. (1982). Percept-percept couplings. *Perception*, 11, 75-83.
- Eriksen, C. W., & St. James, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception and Psychophysics*, 40, 225-240.
- Escher, M. C. (1960). *The Graphic Work of M.C. Escher*. New York: Hawthorn Books.
- Farah, M. J. (1988). Is visual imagery really visual? Overlooked evidence from neuropsychology. *Psychological Review*, 95(3), 307-317.

- Farah, M. J. (1989). Mechanisms of imagery-perception interaction. *Journal of Experimental Psychology: Human Perception and Performance*, 15, 203-211.
- Farah, M. J. (1990). *Visual Agnosia: Disorders of Object Recognition and What They Tell us About Normal Vision*. Cambridge, MA: MIT Press.
- Farah, M. J. (1994). Beyond "pet" methodologies to converging evidence. *Trends in Neurosciences*, 17(12), 514-515.
- Farah, M. J. (1995). The neural bases of mental imagery. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 963-975). Cambridge, MA: MIT Press.
- Farah, M. J., Hammond, K. M., Levine, D. N., & Calvanio, R. (1988). Visual and spatial mental imagery: Dissociable systems of representation. *Cognitive Psychology*, 20(4), 439-462.
- Farah, M. J., Soso, M. J., & Dasheiff, R. M. (1992). Visual angle of the mind's eye before and after unilateral occipital lobectomy. *J Exp Psychol Hum Percept Perform*, 18(1), 241-246.
- Farrell, M. J., & Robertson, I. H. (1998). Mental rotation and the automatic updating of body-centered spatial relationships. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 21, 483-500.
- Felleman, D. J., & Van Essen, D. C. (1991). Distributed hierarchical processing in the primate cerebral cortex. *Cerebral Cortex*, 1(1), 1-47.
- Festinger, L., White, C. W., & Allyn, M. R. (1968). Eye Movements and Decrement in the Muller-Lyer Illusion. *Perception & Psychophysics*, 3(5-B), 376-382.
- Feyerabend, P. (1962). Explanation, reduction and empiricism. In H. Feigl & G. Maxwell (Eds.), *Minnesota Studies in Philosophy of Science (Volume 3)*. Minneapolis, MN: University of Minnesota Press.
- Fidelman, U. (1994). A misleading implication of the metabolism scans of the brain. *Int J Neurosci*, 74(1-4), 105-108.
- Finke, R. A. (1979). The Functional Equivalence of Mental Images and Errors of Movement. *Cognitive Psychology*, 11, 235-264.
- Finke, R. A. (1980). Levels of Equivalence in Imagery and Perception. *Psychological Review*, 87, 113-132.
- Finke, R. A. (1989). *Principles of Mental Imagery*. Cambridge, MA: MIT Press.
- Finke, R. A. (1990). *Creative imagery: Discoveries and inventions in visualization*. Hillsdale, NJ, US: Lawrence Erlbaum Associates, Inc.
- Finke, R. A., & Freyd, J. J. (1989). Mental extrapolation and cognitive penetrability: Reply to Ranney and proposals for evaluative criteria. *Journal of Experimental Psychology: General*, 118(4), 403-408.
- Finke, R. A., & Kosslyn, S. M. (1980). Mental imagery acuity in the peripheral visual field. *J Exp Psychol Hum Percept Perform*, 6(1), 126-139.
- Finke, R. A., & Kurtzman, H. S. (1981a). Mapping the visual field in mental imagery. *J Exp Psychol Gen*, 110(4), 501-517.
- Finke, R. A., & Kurtzman, H. S. (1981b). Methodological considerations in experiments on imagery acuity. *Journal of Experimental Psychology: Human Perception and Performance*, 7(4), 848-855.
- Finke, R. A., & Pinker, S. (1982). Spontaneous imagery scanning in mental extrapolation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 8(2), 142-147.
- Finke, R. A., Pinker, S., & Farah, M. J. (1989). Reinterpreting visual patterns in mental imagery. *Cognitive Science*, 13(1), 51-78.
- Finke, R. A., & Schmidt, M. J. (1977). Orientation-specific color aftereffects following imagination. *Journal of Experimental Psychology: Human Perception & Performance*, 3(4), 599-606.
- Fletcher, P. C., Shallice, T., Frith, C. D., Frackowiak, R. S. J., & Dolan, R. J. (1996). Brain activity during memory retrieval: The influence of imagery and semantic cueing. *Brain*, 119(5), 1587-1596.
- Fodor, J. A. (1968). The Appeal to Tacit Knowledge in Psychological Explanation. *Journal of Philosophy*, 65, 627-640.
- Fodor, J. A. (1975). *The Language of Thought*. New York: Crowell.
- Fodor, J. A. (1981). Imagistic representation. In N. Block (Ed.), *Imagery*. Cambridge, MA: MIT Press.
- Fodor, J. A. (1983). *The Modularity of Mind: An Essay on Faculty Psychology*. Cambridge, Mass.: MIT Press, a Bradford Book.
- Fodor, J. A. (1998). *Concepts: Where cognitive science went wrong*. Oxford: Oxford University Press.
- Fodor, J. A. (2001). Language, Thought and Compositionality. *Mind and Language*, 16(1), 1-15.
- Fodor, J. A., & Pylyshyn, Z. W. (1981). How Direct is Visual Perception? Some Reflections on Gibson's 'Ecological Approach'. *Cognition*, 9, 139-196.

- Fodor, J. A., & Pylyshyn, Z. W. (1988). Connectionism and cognitive architecture: A critical analysis. *Cognition*, 28, 3-71.
- Ford, K., & Pylyshyn, Z. W. (Eds.). (1996). *The Robot's Dilemma Revisited*. Stamford, CT: Ablex Publishers.
- Fox, E. (1995). Negative priming from ignored distractors in visual selection: A review. *Psychonomic Bulletin & Review*, 2(2), 145-173.
- Fox, P. T., Mintun, M. A., Raichle, M. E., Miezin, F. M., Allman, J. M., & Van Essen, D. C. (1986). Mapping human visual cortex with positron emission tomography. *Nature*, 323(6091), 806-809.
- Fraisse, P. (1963). *The Psychology of Time*. New York: Harper & Row.
- Freuder, E. C. (1986). Knowledge-Mediated Perception. In H. C. Nusbaum, and Schwab, E. C. (Ed.), *Pattern Recognition by Humans and Machines: Visual Perception* (Vol. 2). Orlando: Academic Press Inc.
- Freyd, J. J., & Finke, R. A. (1984). Representational momentum. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 10(1), 126-132.
- Friedman, A. (1978). Memorial comparisons without the "mind's eye." *Journal of Verbal Learning & Verbal Behavior*, 17(4), 427-444.
- Friedman-Hill, S., & Wolfe, J. M. (1995). Second-order parallel processing: Visual search for odd items in a subset. *Journal of Experimental Psychology: Human Perception and Performance*, 21(3), 531-551.
- Frisby, J. P., & Clatworthy, J. L. (1975). Learning to see complex random-dot stereograms. *Perception*, 4(2), 173-178.
- Galilei, G. (1610/1983). The starry messenger. In S. Drake (Ed.), *Telescopes, Tides & Tactics*. Chicago: University of Chicago Press.
- Gallistel, C. R. (1990). *The Organization of Learning*. Cambridge, MA: MIT Press (A Bradford Book).
- Gallistel, C. R. (1994). Foraging for brain stimulation: Toward a neurobiology of computation. *Cognition*, 50, 151-170.
- Gallistel, C. R., & Cramer, A. E. (1996). Computations on metric maps in mammals: Getting oriented and choosing a multi-destination route. *Journal of Experimental Biology*, 199(1), 211-217.
- Gardner, M. (1982). *Logic machines and diagrams* (second ed.). Chicago: University of Chicago Press.
- Gazzaniga, M. S. (2000). Cerebral specialization and interhemispheric communication: Does the corpus callosum enable the human condition? *Brain*, 123(7), 1293-1326.
- Georgeff, M. P. (1987). Planning. In J. F. Traub & B. J. Grosz & B. W. Lampson & N. J. Nilsson (Eds.), *Annual Review of Computer Science* (Vol. 2). Palo Alto: Annual Reviews Inc.
- Getzels, J. W., & Jackson, P. W. (1962). *Creativity and intelligence: Explorations with gifted students*: NY: Wiley. (1962). xvii, 293pp.
- Gibson, B. (1994). Visual attention and objects: One versus two or convex versus concave? *Journal of Experimental Psychology: Human Perception and Performance*, 20, 203-207.
- Gibson, E. J. (1991). *An Odyssey in learning and perception*. Cambridge, MA: MIT Press.
- Gibson, J. J. (1966). *The Senses Considered as Perceptual Systems*. Boston: Houghton Mifflin.
- Gibson, J. J. (1979). *An Ecological Approach to Visual Perception*. Boston: Houghton Mifflin.
- Gilchrist, A. (1977). Perceived lightness depends on perceived spatial arrangement. *Science*, 195, 185-187.
- Gilden, D., Blake, R., & Hurst, G. (1995). Neural adaptation of imaginary visual motion. *Cognitive Psychology*, 28(1), 1-16.
- Gillam, B., & Chambers, D. (1985). Size and position are incongruous: Measurements on the Mueller-Lyer figure. *Perception & Psychophysics*, 37(6), 549-556.
- Girgus, J. J., Rock, I., & Egatz, R. (1977). The effect of knowledge of reversibility on the reversibility of ambiguous figures. *Perception and Psychophysics*, 22(6), 550-556.
- Gnadt, J. W., Bracewell, R. M., & Anderson, R. A. (1991). Sensorimotor transformation during eye movements to remembered visual targets. *Vision Research*, 31, 693-715.
- Gogel, W. C. (1997/1973). The organization of perceived space. In I. Rock (Ed.), *Indirect Perception* (pp. 361-386). Cambridge, MA: MIT Press.
- Goldenberg, G. (1992). Loss of visual imagery and loss of visual knowledge--a case study. *Neuropsychologia*, 30(12), 1081-1099.
- Goldenberg, G., & Artner, C. (1991). Visual imagery and knowledge about the visual appearance of objects in patients with posterior cerebral artery lesions. *Brain and Cognition*, 15(2), 160-186.
- Goldenberg, G., Mullbacher, W., & Nowak, A. (1995). Imagery without perception--a case study of anosognosia for cortical blindness. *Neuropsychologia*, 33(11), 1373-1382.

- Goldstone, R. L. (1994). Influences of categorization on perceptual discrimination. *Journal of Experimental Psychology: General*, 123(2), 178-200.
- Goldstone, R. L. (1995). The effect of categorization on color perception. *Psychological Science*, 6(5), 298-304.
- Gollin, E. S. (1960). Developmental studies of visual recognition of incomplete objects. *Perceptual and Motor Skills*, 11, 289-298.
- Goodale, M. A. (1983). Vision as a sensorimotor system. In T. E. Robinson (Ed.), *Behavioral approaches to brain research* (pp. 41-61). New York: Oxford University Press.
- Goodale, M. A. (1988). Modularity in visuomotor control: From input to output. In Z. W. Pylyshyn (Ed.), *Computational Processes in Human Vision: An interdisciplinary perspective* (pp. 262-285). Norwood, NJ: Ablex Publishing.
- Goodale, M. A., Jacobson, J. S., & Keillor, J. M. (1994). Differences in the visual control of pantomimed and natural grasping movements. *Neuropsychologia*, 32(10), 1159-1178.
- Goodale, M. A., & Milner, A. D. (1982). Fractionating orientation behavior in rodents. In M. A. G. d. J. Ingle, & r. J. W. Mansfield (Ed.), *Analysis of visual behavior*. Cambridge, MA: MIT Press.
- Goodale, M. A., Pelisson, D., & Prablanc, C. (1986). Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. *Nature*, 320, 748-750.
- Goodman, N. (1968). *Languages of Art*. Indianapolis: Bobbs-Merrill.
- Gordon, R. D., & Irwin, D. E. (1996). What's in an object file? Evidence from priming studies. *Perception and Psychophysics*, 58(8), 1260-1277.
- Goryo, K., Robinson, J. O., & Wilson, J. A. (1984). Selective looking and the Mueller-Lyer illusion: The effect of changes in the focus of attention on the Mueller-Lyer illusion. *Perception*, 13(6), 647-654.
- Gosselin, F., & Schyns, P. G. (in press). Superstitious perceptions reveal properties of internal representations. *Psychological Science*.
- Green, B. F., & Anderson, L. K. (1956). Color coding in a visual search task. *Journal of Experimental Psychology*, 51, 19-24.
- Greenfield, P. M., deWinstanley, P., Kilpatrick, H., & Kaye, D. (1994). Action video games and informal education: effects on strategies for dividing visual attention. Special issue: Effects of interactive entertainment technologies on development. *Journal of Applied Developmental Psychology*, 15(1), 105-123.
- Gregory, R. L. (1970). *The Intelligent Eye*. New York: McGraw-Hill.
- Grice, H. P. (1975). Logic and Conversation. *Syntax and Semantics*, 3, 41-58.
- Grimes, J. (1996). Failure to detect changes in scenes across saccades. In K. Akins (Ed.), *Perception*. New York: Oxford University Press.
- Grimson, W. E. L. (1990). The combinatorics of object recognition in cluttered environment using constrained search. *Artificial Intelligence*, 44(1-2), 121-166.
- Guariglia, C., Padovani, A., Pantano, P., & Pizzamiglio, L. (1993). Unilateral neglect restricted to visual imagery. *Nature*, 364(6434), 235-237.
- Gumperz, J., & Levinson, S. (Eds.). (1996). *Rethinking Linguistic Relativity: Studies in the social and cultural foundations of language*. Cambridge, UK: Cambridge University Press.
- Haber, R. N. (1966). Nature of the effect of set on perception. *Psychological Review*, 73, 335-351.
- Haber, R. N. (1968). Perceptual reports vs recognition responses: A reply to Parks. *Perception & Psychophysics*, 4(6), 374.
- Haber, R. N. (1979). Twenty years of haunting eidetic imagery: Where's the ghost? *Behavioral & Brain Sciences*, 2(4), 583-629.
- Haber, R. N., & Nathanson, L. S. (1968). Post-retinal storage? Some further observations on Park's Camel as seen through the eye of a needle. *Perception and Psychophysics*, 3, 349-355.
- Haenny, P., & Schiller, P. (1988). State dependent activity in monkey visual cortex I. Single cell activity in V1 and V4 on visual tasks. *Experimental Brain Research*, 69, 225-244.
- Hagenzieker, M. P., van der Heijden, A. H. C., & Hagenaar, R. (1990). Time course in visual-information processing: some empirical evidence for inhibition. *Psychological Research*, 52, 13-21.
- Haier, R. J., Siegel, B. V., Neuchterlein, K. H., Hazlett, E., Wu, J. C., Paek, J., Browning, H. L., & Buchsbaum, M. S. (1988). Cortical glucose metabolic rate correlates of abstract reasoning and attention studied with positron emission tomography. *intelligence*, 12, 199-217.
- Hampson, P. J., & Duffy, C. (1984). Verbal and spatial interference effects in congenitally blind and sighted subjects. *Canadian Journal of Psychology*, 38(3), 411-420.

- Hans, M. A. (1974). Imagery and modality in paired-associate learning in the blind. *Bulletin of the Psychonomic Society*, 4(1), 22-24.
- Hanson, N. R. (1958). *Patterns of Discovery*. Cambridge: Cambridge University Press.
- Harper, W. L., Stalnaker, R., & Pearce, G. (Eds.). (1981). *Ifs: Conditionals, belief, decision, chance and time*. Boston, MA: D. Reidel.
- Harris, J. P. (1982). The VVIQ imagery-induced McCollough effects: an alternative analysis. *Percept Psychophys*, 32(3), 290-292.
- Harrison, J. E., & Baron-Cohen, S. (1997). Synaesthesia: A review of psychological theories. In S. Baron-Cohen & J. E. Harrison (Eds.), *Synaesthesia: Classic and Contemporary Readings* (pp. 109-122). Cambridge, MA: Blackwell.
- Hayes, J. R. (1973). On the Function of Visual Imagery in Elementary Mathematics. In W. G. Chase (Ed.), *Visual Information Processing*. New York: Academic Press.
- Hayes, J. R., & Simon, H. A. (1976). The Understanding Process: Problem Isomorphs. *Cognitive Psychology*, 8, 165-180.
- Hayhoe, M. M., Bensinger, D. G., & Ballard, D. H. (1997). Visual memory in natural tasks. *Vision Research*.
- He, S., Cavanagh, P., & Intriligator, J. (1997). Attentional resolution. *Trends in Cognitive Sciences*, 1(3), 115-121.
- He, Z. J., & Nakayama, K. (1994). Perceiving textures: Beyond filtering. *Vision Research*, 34, 151-162.
- Hebb, D. O. (1949). *Organization of Behavior*. New York: Wiley.
- Heller, M. A., & Kennedy, J. M. (1990). Perspective taking, pictures, and the blind. *Perception & Psychophysics*, 48(5), 459-466.
- Henderson, J. M. (1991). Stimulus discrimination following covert attentional orienting to an exogenous cue. *Journal of Experimental Psychology: Human Perception and Performance*, 11, 409-430.
- Henderson, J. M., & Hollingworth, A. (1999). The role of fixation position in detecting scene changes across saccades. *Psychological Science*, 10(5), 438-443.
- Hernandez-Péon, R., Scherrer, R. H., & Jouvet, M. (1956). Modification of electrical activity in the cochlear nucleus during "attention" in unanesthetized cats. *Science*, 123, 331-332.
- Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993). Voluntary and stimulus-induced attention detected as motion sensation. *Perception*, 22, 517-526.
- Hinton, G. E. (1987). The horizontal-vertical delusion. *Perception*, 16(5), 677-680.
- Hirsch, E. (1982). *The Concept of Identity*. Oxford, UK: Oxford.
- Hochberg, J. (1968). In the mind's eye. In R. N. Haber (Ed.), *Contemporary theory and research in visual perception* (pp. 309-331). New York: Holt, Rinehart & Winston.
- Hochberg, J., & Gellman, L. (1977). The effect of landmark features on mental rotation times. *Memory & Cognition*, 5(1), 23-26.
- Hoening, P. (1972). The effects of eye movements, fixation and figure size on decrement in the Muller-Lyer illusion. *Dissertation Abstracts International*, 33(6-B), 2835.
- Hoffman, D. D. (1998). *Visual Intelligence: How We Create What We See*. New York: W.W. Norton.
- Hollingworth, A., & Henderson, J. M. (1999). Vision and cognition: Drawing the line. *Behavioral and Brain Sciences*, 22(3), 380-381.
- Hollingworth, A., & Henderson, J. M. (in press). Does consistent scene context facilitate object perception? *Journal of Experimental Psychology: General*.
- Holmes, G. (1918). Disturbances in visual orientation. *British Journal of Ophthalmology*, 2, 449-506.
- Holmes, G., & Horax, G. (1919). Disturbances of spatial orientation and visual attention, with loss of stereoscopic vision. *Archives of Neurology and Psychiatry*, 1, 385-407.
- Howard, I. P. (1982). *Human Visual Orientation*. New York, NY: John Wiley & Sons.
- Howard, R. J., ffytche, D. H., Barnes, J., McKeefry, D., Ha, Y., Woodruff, P. W., Bullmore, E. T., Simmons, A., Williams, S. C., David, A. S., & Brammer, M. (1998). The functional anatomy of imagining and perceiving colour. *Neuroreport*, 9(6), 1019-1023.
- Hubel, D. H., & Wiesel, T. N. (1962). Receptive fields, binocular interaction, and functional architecture in the cat's visual cortex. *Journal of Physiology*, 160, 106-154.
- Humphrey, G. (1951). *Thinking: An introduction to its experimental psychology*. London: Methuen.
- Humphreys, G. W., & Riddoch, M. J. (1987). *To see but not to see: a case study of visual agnosia*. Hillsdale, NJ: Lawrence Erlbaum.

- Humphreys, G. W., & Riddoch, M. J. (1993). Interactions between object and space systems revealed through neuropsychology. In D. Meyer & S. Kornblum (Eds.), *Attention and Performance XIV* (pp. 183-218). Cambridge, MA: MIT Press.
- Humphreys, G. W., & Riddoch, M. J. (1994). Visual object processing in normality and pathology: Implications for rehabilitation. In G. W. H. M. Jane Riddoch (Ed.), *Cognitive neuropsychology and cognitive rehabilitation* (pp. 39-76). Hove, England: Lawrence Erlbaum Associates, Inc.
- Humphreys, G. W., & Riddoch, M. J. (1995). Separate coding of space within and between perceptual objects: Evidence from unilateral visual neglect. *Cognitive Neuropsychology*, *12*, 283-311.
- Huttenlocher, J. (1968). Constructing spatial images: A strategy in reasoning. *Psychological Review*, *75*(6), 550-560.
- Ingle, D. J. (1973). Two visual systems in the frog. *Science*, *181*, 1053-1055.
- Ingle, D. J., Goodale, M. A., & Mansfield, R. J. W. (Eds.). (1982). *Analysis of visual behavior*. Cambridge, MA: MIT Press.
- Intons-Peterson, M. J. (1983). Imagery paradigms: How vulnerable are they to experimenters' expectations? *Journal of Experimental Psychology: Human Perception & Performance*, *9*(3), 394-412.
- Intons-Peterson, M. J., & White, A. R. (1981). Experimenter naivete and imaginal judgments. *Journal of Experimental Psychology: Human Perception & Performance*, *7*(4), 833-843.
- Intriligator, J., & Cavanagh, P. (1992). Object-specific spatial attention facilitation that does not travel to adjacent spatial locations. *Investigative Ophthalmology and Visual Science*, *33*, 2849 (abstract).
- Intriligator, J. M. (1997). *The spatial resolution of attention*. Unpublished Ph.D., Harvard, Cambridge, MA.
- Irwin, D. E. (1991). Information integration across saccadic eye movements. *Cognitive Psychology*, *23*, 420-456.
- Irwin, D. E. (1993). Perceiving an integrated visual world. In D. E. Meyer & S. Kornblum (Eds.), *Attention and Performance XIV*. Cambridge, MA: MIT Press.
- Irwin, D. E. (1996). Integrating information across saccadic eye movements. *Current Directions in Psychological Science*, *5*(3), 94-100.
- Irwin, D. E., McConkie, G. W., Carlson-Radvansky, L. A., & Currie, C. (1994). A localist evaluation solution for visual stability across saccades. *Behavioral and Brain Sciences*, *17*, 265-266.
- Ishai, A., & Sagi, D. (1995). Common mechanisms of visual imagery and perception. *Science*, *268*(5218), 1772-1774.
- Ittelson, W. H., & Ames, A. J. (1968). *The Ames Demonstrations in Perception*. New York: Hafner Publishing Co.
- Jamnek, M. (2001). *Mathematical reasoning with diagrams: from intuition to automation*. Chicago, IL: U of Illinois Press (distributor).
- Jankowiak, J., Kinsbourne, M., Shalev, R. S., & Bachman, D. L. (1992). Preserved visual imagery and categorization in a case of associative visual agnosia. *Journal of Cognitive Neuroscience*, *4*(2), 119-131.
- Jensen, E., Reese, E., & Reese, T. (1950). The subitizing and counting of visually presented fields of dots. *Journal of Psychology*, *30*, 363-392.
- Johansson, G. (1950). *Configurations in Event Perception*. Boston: Houghton Mifflin.
- Johnson, M. H., & Gilmore, R. O. (1998). Object-centered attention in 8-month-old infants. *Developmental Science*, *1*(2), 221-225.
- Johnson, R. A. (1980). Sensory images in the absence of sight: Blind versus sighted adolescents. *Perceptual & Motor Skills*, *51*(1), 177-178.
- Johnson-Laird, P. N. (1989). Mental models. In M. I. Posner (Ed.), *Foundations of cognitive science*. (pp. 469-499). Cambridge, MA, US: The MIT Press.
- Johnson-Laird, P. N. (2001). Mental models and deduction. *Trends in Cognitive Sciences*, *5*(10), 434-442.
- Jolicoeur, P., S. Ullman, and M. F. MacKay. (1983). *Boundary Tracing: An Elementary Visual Process* (unpub. manuscript): University of Saskatchewan.
- Jonides, J., Kahn, R., & Rozin, P. (1975). Imagery instructions improve memory in blind subjects. *Bulletin of the Psychonomic Society*, *5*(5), 424-426.
- Julesz, B. (1971). *Foundations of Cyclopean Perception*. Chicago: Univ. of Chicago Press.
- Julesz, B. (1990). Early vision is bottom up, except for focal attention. *Cold Spring Harbor Symposium on Quantitative Biology*, *55*, 973-978.
- Julesz, B., & Pappathomas, T. V. (1984). On spatial-frequency channels and attention. *Perception and Psychophysics*, *36*(4), 398-399.
- Just, M. A., & Carpenter, P. A. (1976). Eye fixations and cognitive processes. *Cognitive Psychology*, *8*(4), 441-480.

- Kabanza, F., Barbeau, M., & St-Denis, R. (1997). Planning control rules for reactive agents. *Artificial Intelligence*, 95, 67-113.
- Kahneman, D., & Treisman, A. (1984). Changing views of attention and automaticity. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of Attention* (pp. 29-62). New York: Academic Press.
- Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive Psychology*, 24(2), 175-219.
- Kanizsa, G. (1969). Perception, past experience and the impossible experiment. *Acta Psychologica*, 31, 66-96.
- Kanizsa, G. (1976). Subjective contours. *Scientific American*, 234, 48-52.
- Kanizsa, G. (1985). Seeing and Thinking. *Acta Psychologica*, 59, 23-33.
- Kanizsa, G., & Gerbino, W. (1982). Amodal completion: Seeing or thinking? In B. Beck (Ed.), *Organization and Representation in Perception* (pp. 167-190). Hillsdale, NJ: Erlbaum.
- Kant, E. (1998). *The Critique of Pure Reason (Kritik der reinen Vernunft. English)* (P. Guyer & A. Wood, Trans.). Cambridge, UK: Cambridge University Press.
- Kanwisher, N. (2001). Neural events and perceptual awareness. *Cognition*, 79, 89-113.
- Karni, A., & Sagi, D. (1995). A memory system in the adult visual cortex. In B. Julesz & I. Kovacs (Eds.), *Maturation Windows and adult cortical plasticity* (pp. 95-109). Reading, MA: Addison-Wesley.
- Kaufman, E., Lord, M., Reese, T., & Volkman, J. (1949). The discrimination of visual number. *American Journal of Psychology*, 62, 498-525.
- Kawabata, N. (1986). Attention and depth perception. *Perception*, 15(5), 563-572.
- Kelly, M. D. (1971). Edge detection by computer using planning. In B. Meltzer & D. Michie (Eds.), *Machine Intelligence 6*. Edinburgh: University of Edinburgh Press.
- Kelso, J. A. S., Cook, E., Olson, M. E., & Epstein, W. (1975). Allocation of attention and the locus of adaptation to displaced vision. *Journal of Experimental Psychology: Human Perception and Performance*, 1, 237-245.
- Kerr, N. H. (1983). The role of vision in "visual imagery" experiments: Evidence from the congenitally blind. *Journal of Experimental Psychology: General*, 112(2), 265-277.
- Klein, G., & Crandall, B. W. (1995). The role of mental simulation in problem solving and decision making. In P. Hancock (Ed.), *Local applications of the ecological approach to human-machine systems, Volume 2: Resources for ecological psychology* (Vol. 2, pp. 324-358). Mahwah, NJ: Lawrence Erlbaum Associates.
- Klein, R. (2000). Inhibition of return. *Trends in Cognitive Sciences*, 4(4), 138-147.
- Koch, C., & Ullman, S. (1985). Shifts in selective visual attention: towards the underlying neural circuitry. *Human Neurobiology*, 4, 219-227.
- Koenderink, J. J. (1990). *Solid Shape*. Cambridge, MA: MIT Press.
- Kosslyn, S. M. (1978). Measuring the visual angle of the mind's eye. *Cognitive Psychology*, 10, 356-389.
- Kosslyn, S. M. (1981). The Medium and the Message in Mental Imagery: A Theory. *Psychological Review*, 88, 46-66.
- Kosslyn, S. M. (1994). *Image and Brain: The resolution of the imagery debate*. Cambridge, MA: MIT Press.
- Kosslyn, S. M., Ball, T. M., & Reiser, B. J. (1978). Visual images preserve metric spatial information: Evidence from studies of image scanning. *Journal of Experimental Psychology: Human Perception and Performance*, 4, 46-60.
- Kosslyn, S. M., Pascual-Leone, A., Felican, O., Camposano, S., Keenan, J. P., Thompson, W. L., Ganis, G., Sukel, K. E., & Alpert, N. M. (1999a). The role of area 17 in visual imagery: Convergent evidence from PET and rTMS. *Science*, 284(April 2), 167-170.
- Kosslyn, S. M., Pinker, S., Smith, G., & Shwartz, S. P. (1979). On the demystification of mental imagery. *Behavioral and Brain Science*, 2, 535-581.
- Kosslyn, S. M., Sukel, K. E., & Bly, B. M. (1999b). Squinting with the mind's eye: Effects of stimulus resolution on imaginal and perceptual comparisons. *Memory & Cognition*, 27(2), 276-287.
- Kosslyn, S. M., & Sussman, A. L. (1995). Roles of imagery in perception: or, There is no such thing as immaculate perception. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 1035-1042). Cambridge, MA: MIT Press.
- Kosslyn, S. M., Thompson, W. L., Kim, I. J., & Alpert, N. M. (1995). Topographical representations of mental images in primary visual cortex. *Nature*, 378(Nov 30), 496-498.
- Kotovsky, K., Hayes, J. R., & Simon, H. A. (1985). Why are some problems hard? Evidence from Tower of Hanoi. *Cognitive Psychology*, 17(2), 248-294.
- Kowler, E. (1989). Cognitive expectations, not habits, control anticipatory smooth oculomotor pursuit. *Vision Research*, 29, 1049-1057.

- Kowler, E. (1990). The role of visual and cognitive processes in the control of eye movement. In E. Kowler (Ed.), *Eye movements and their role in visual and cognitive processes* (pp. 1-70). Amsterdam: Elsevier Science Publishers.
- Kowler, E., Anderson, E., Doshier, B., & Blaser, E. (1995). The role of attention in the programming of saccades. *Vision Research*, 35(13), 1897-1916.
- Kowler, E., & Steinman, R. M. (1977). The role of small saccades in counting. *Vision Research*, 17(1), 141-146.
- Kubovy, M., & Van Valkenburg, D. (2001). Auditory and visual objects. *Cognition*, 80(1/2), 97-126.
- Kuhn, T. (1972). *The Structure of Scientific Revolutions*. Chicago: Univ. of Chicago Press.
- Kunen, S., & May, J. G. (1980). Spatial frequency content of visual imagery. *Perception & Psychophysics*, 28(6), 555-559.
- Kunen, S., & May, J. G. (1981). Imagery-induced McCollough effects: Real or imagined? *Perception & Psychophysics*, 30(1), 99-100.
- Lackner, J. R., & Garrett, M. F. (1972). Resolving ambiguity: Effects of biasing context in the unattended ear. *Cognition*, 1, 359-372.
- Landis, T. (2000). Disruption of space perception due to cortical lesions. *Spatial Vision*, 13(2-3), 179-191.
- Lee, D. N., & Lishman, J. R. (1975). Visual proprioceptive control of stance. *Journal of Human Movement Studies*, 1, 87-95.
- Lee, E. K. B., & Simon, H. (1993). Parallel implementation of the extended square-root covariance filter for tracking applications. *IEEE Transactions on Parallel & Distributed Systems*, 4, 446-457.
- Leslie, A. M., Xu, F., Tremolet, P. D., & Scholl, B. J. (1998). Indexing and the object concept: Developing 'what' and 'where' systems. *Trends in Cognitive Sciences*, 2(1), 10-18.
- Lespérance, Y., & Levesque, H. J. (1995). Indexical knowledge and robot action - a logical account. *Artificial Intelligence*, 73, 69-115.
- Levesque, H. (1986). Making believers out of computers. *Artificial Intelligence*, 30, 81-108.
- Leyton, M. (1992). *Symmetry, causality, mind*. Cambridge, MA, USA: Mit Press.
- Li, P., & Gleitman, L. (2002). Turning the tables: Language and spatial reasoning. *Cognition*, 83, 265-294.
- Lindsay, P. H., & Norman, D. A. (1977). *Human Information Processing: An Introduction to Psychology* (Second edition ed.). New York: Academic Press.
- Livingstone, M. S., & Hubel, D. H. (1987). Psychophysical evidence for separate channels for the perception of form, color, movement, and depth. *The Journal of Neuroscience*, 7(11), 3416-3468.
- Loftus, E. F. (1975). Leading questions and the eyewitness report. *Cognitive Psychology*, 7, 560-572.
- Lowe, D. G. (1987). Three-dimensional object recognition from single two-dimensional images. *Artificial Intelligence*, 31, 355-395.
- Luce, R. D., D'Zmura, M., Hoffman, D. D., Iverson, G. J., & Romney, A. K. (Eds.). (1995). *Geometric representations of perceptual phenomena: Papers in honor of Tarow Indow on his 70th birthday* (Vol. 356). Mahwah, NJ, USA: Lawrence Erlbaum Associates, Inc.
- Luchins, A. S. (1942). Mechanization in problem solving. *Psychological Monographs*, 54(6), Whole No. 248.
- Luck, S., & Vogel, E. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, 390, 279-281.
- Luria, A. R. (1959). Disorders of 'simultaneous perceptio n' in a case of bilateral occipito-parietal brain injury. *Brain*, 83, 437-449.
- Lynch, J. C. (1980). The functional organization of posterior parietal cortex. *Behavioral and Brain Sciences*, 3, 485-534.
- Mack, A., Heuer, F., Villardi, K., & Chambers, D. (1985). The dissociation of position and extent in Mueller-Lyer figures. *Perception & Psychophysics*, 37(4), 335-344.
- Mack, A., & Rock, I. (1998a). *Inattentional blindness*. Cambridge, MA: Mit Press.
- Mack, A., & Rock, I. (1998b). Inattentional blindness: Perception without attention. In R. D. Wright (Ed.), *Visual Attention*. New York: Oxford University Press.
- Mackworth, A. K. (1973). Interpreting Pictures fo Polyhedral Scenes. *Artificial Intelligence*, 4, 121-137.
- Maloney, L. T., & Wandell, B. A. (1990). Color constancy: A method for recovering surface spectral reflectance. In S. Ullman & W. Richards (Eds.), *Image Understanding 1989* (Vol. 3). Norwood, NJ: Ablex Publishing.
- Mandler, G., & Shebo, B. (1982). Subitizing: An analysis of its component processes. *Journal of Experimentlta Psychology: General*, 111, 1-22.
- Mani, K., & Johnson-Laird, P. N. (1982). The mental representation of spatial descriptions. *Memory & Cognition*, 10(2), 181-187.

- Marmor, G. S., & Zaback, L. A. (1976). Mental rotation by the blind: Does mental rotation depend on visual imagery? *Journal of Experimental Psychology: Human Perception & Performance*, 2(4), 515-521.
- Marr, D. (1982). *Vision: A computational investigation into the human representation and processing of visual information*. San Francisco: W.H. Freeman.
- Marr, D., & Nishihara, H. K. (1976). *Representation and recognition of spatial organization of three-dimensional shapes*.
- Marr, D., & Poggio, T. (1979). A theory of human stereo vision. *Proceedings of the Royal Society of London*, 204(1156), 301-328.
- Marshall, J. C. (2001). Auditory neglect and right parietal cortex. *Brain*, 124(4), 645-646.
- Mather, J. A., & Lackner, J. R. (1977). Adaptation to visual rearrangement: Role of sensory discordance. *Quarterly Journal of Experimental Psychology*, 29(2), 237-244.
- Mather, J. A., & Lackner, J. R. (1980). Visual tracking of active and passive movements of the hand. *Quarterly Journal of Experimental Psychology*, 32(2), 307-315.
- Mather, J. A., & Lackner, J. R. (1981). Adaptation to visual displacement: Contribution of proprioceptive, visual, and attentional factors. *Perception*, 10(4), 367-374.
- McBeath, M. K., Shaffer, D. M., & Kaiser, M. K. (1995). How baseball outfielders determine where to run to catch fly balls. *Science*, 278(April 28), 569-573.
- McConkie, G. M., & Currie, C. B. (1996). Visual stability across saccades while viewing complex pictures. *Journal of Experimental Psychology: Human Perception and Performance*, 22(3), 563-581.
- McCormick, P. A., & Klein, R. (1990). The spatial distribution of attention during covert visual orienting. *Acta Psychologica*, 75, 225-242.
- McGinn, C. (1999). *The mysterious flame: Conscious minds in a material world*. New York, NY, USA: Basic Books, Inc.
- McGlinchey-Berroth, R., Milberg, W. P., Verfaellie, M., & Grande, L. (1996). Semantic processing and orthographic specificity in hemispatial neglect. *Journal of Cognitive Neuroscience*, 8(3), 291-304.
- McKeever, P. (1991). *Nontarget numerosity and identity maintenance with FINSTs: A two component account of multiple-target tracking*. Unpublished MA Dissertation, University of Western Ontario, London, Canada.
- McKelvie, S. J. (1994). The Validity of Visual Imagery Questionnaire as a predictor of facial recognition memory performance. *Br J Psychol*, 85(Pt 1), 93-104.
- McKim, R. H. (1978). The Imaginarium: An environment and program for opening the mind's eye. In B. S. Randhawa & W. E. Coffman (Eds.), *Visual Learning, Thinking and Communication* (pp. 61-91). New York: Academic Press.
- McLeod, P., Driver, J., Dienes, Z., & Crisp, J. (1991). Filtering by movement in visual search. *Journal of Experimental Psychology: Human Perception & Performance*, 17(1), 55-64.
- Mellet, E., Petit, L., Mazoyer, B., Denis, M., & Tzourio, N. (1998). Reopening the mental imagery debate: lessons from functional anatomy. *Neuroimage*, 8(2), 129-139.
- Mellet, E., Tzourio, N., Crivello, F., Joliot, M., Denis, M., & Mazoyer, B. (1996). Functional anatomy of spatial mental imagery generated from verbal instructions. *Journal of Neuroscience*, 16(20), 6504-6512.
- Merikle, P. M., Smilek, D., & Eastwood, J. D. (2001). Perception without awareness: perspectives from cognitive psychology. *Cognition*, 79, 115-134.
- Michie, D. (1986). *On Machine Intelligence* (Second ed.). New York: Halstead Press.
- Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, 63, 81-97.
- Miller, G. A. (1962). Decision units in the perception of speech. *Institute of Radio Engineers: Transactions on Information Theory*, 8, 81-83.
- Miller, G. A. (1984). Informavores. In F. Machlup & U. Mansfield (Eds.), *The Study of Information: Interdisciplinary Messages*. New York: Wiley.
- Miller, G. A., Bruner, J. S., & Postman, L. (1954). Familiarity of letter sequences and tachistoscopic identification. *Journal of General Psychology*, 50, 129-139.
- Miller, J., & Festinger, L. (1977). Impact of oculomotor retraining on the visual perception of curvature. *Journal of Experimental Psychology: Human Perception & Performance*, 3(2), 187-200.
- Miller, N. (2001). *A Diagrammatic Formal System for Euclidean Geometry*. Unpublished Ph.D., Cornell University, Ithica, NY.
- Milner, A. D., & Goodale, M. A. (1995). *The Visual Brain in Action*. New York: Oxford University Press.

- Mitchell, D. B., & Richman, C. L. (1980). Confirmed reservations: Mental travel. *Journal of Experimental Psychology: Human Perception and Performance*, 6, 58-66.
- Moffatt, H. K. (2000). Euler's disk and its finite-time singularity. *Nature*, 404(6780), 833-834.
- Moore, C., Yantis, S., & Vaughan, B. (1998). Object-based visual selection: Evidence from perceptual completion. *Psychological Science*, 9, 104-110.
- Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science*, 229(4715), 782-784.
- Morton, J., Hammersley, R. H., & Bekerian, D. A. (1985). Headed records: A model for memory and its failures. *Cognition*, 20(1), 1-23.
- Mountcastle, V., Motter, B., Steinmetz, M., & Sestokas, A. (1987). Common and differential effects of attentive fixation on the excitability of parietal and prestriate (V4) cortical visual neurons in the macaque monkey. *Journal of Neuroscience*, 7(7), 2239-2255.
- Mueller, H. J., & Findlay, J. M. (1988). The effect of visual attention on peripheral discrimination thresholds in single and multiple element displays. *Acta Psychologica*, 69(2), 129-155.
- Mueller, H. J., & Rabbitt, P. M. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception & Performance*, 15(2), 315-330.
- Nakayama, K., He, Z. J., & Shimojo, S. (1995). Visual surface representation: A critical link between lower-level and higher-level vision. In S. M. Kosslyn & D. N. Osherson (Eds.), *Visual Cognition* (Second ed., pp. 1-70). Cambridge, MA: MIT Press.
- Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, 29, 1631-1647.
- Nakayama, K., & Silverman, G. H. (1986). Serial and parallel processing of visual feature conjunctions. *Nature*, 320(6059), 264-265.
- Nazir, T. A., & O'Regan, J. K. (1990). Some results on translation invariance in the human visual system. *Spatial Vision*, 5(2), 81-100.
- Neisser, U., & Becklen, R. (1975). Selective looking: attending to visually specified events. *Cognitive psychology*, 7, 480-494.
- Newell, A. (1972). A Theoretical Exploration of Mechanisms for Coding the Stimulus. In A. W. M. a. E. Martin (Ed.), *Coding Processes in Human Memory*. Edinburgh: Edinburgh Univ. Press.
- Newell, A. (1980a). HARP, Production Systems, and Human Cognition. In R. A. Cole (Ed.), *Perception and production of fluent speech*. Hillsdale, NJ: Erlbaum.
- Newell, A. (1980b). Physical Symbol Systems. *Cognitive Science*, 4(2), 135-183.
- Newell, A. (1990). *Unified Theories of Cognition*. Cambridge, MA: Harvard University Press.
- Newell, A., & Simon, H. A. (1972). *Human Problem Solving*. Englewood Cliffs, N.J.: Prentice-Hall.
- Nichols, S., Stich, S., Leslie, A., & Klein, D. (1996). Varieties of on-line simulation. In P. Carruthers & P. Smith (Eds.), *Theories of theories of mind* (pp. 39-74). Cambridge, UK: Cambridge University Press.
- Nicod, J. (1970). *Geometry and Induction*. Berkeley: Univ. of California Press.
- Nijhawan, R. (1991). Three-dimensional Muller-Lyer Illusion. *Perception & Psychophysics*, 49(9), 333-341.
- Nijhawan, R. (1994). Motion extrapolation in catching. *Nature*, 370(6487), 256-257.
- Nissen, M. J. (1985). Accessing features and objects: Is location special? In M. I. Posner & O. S. Marin (Eds.), *Attention and performance XI* (pp. 205-219). Hillsdale, NJ: Lawrence Erlbaum.
- Norman, D. A. (1969). *Memory and Attention*. New York: Wiley.
- Norman, D. A. (1988). *The psychology of everyday things*: New York, NY, US: Basic Books, Inc. (1988). xi, 257pp.
- Norman, D. A. (1991). Cognitive artifacts. In J. M. Carroll (Ed.), *Designing interaction: Psychology at the human-computer interface* (pp. 17-38). New York, NY, US: Cambridge University Press; Cambridge University Press.
- Nougier, V., Ripoll, H., & Stein, J.-F. (1989). Orienting of attention with highly skilled athletes. *International Journal of Sport Psychology*, 20(3), 205-223.
- Ogawa, H., & Yagi, A. (2002). *The processing of untracked objects during multiple object tracking*. Paper presented at the Vision Sciences 2002, Sarasota, FL.
- Ohkuma, Y. (1986). A comparison of image-induced and perceived Mueller-Lyer illusion. *Journal of Mental Imagery*, 10(4), 31-38.

- O'Kane, B. L., Biederman, I., Cooper, E. E., & Nystrom, B. (1997). An account of objects identification confusions. *Journal of Experimental Psychology: Applied*, 3(1), 21-41.
- Olivers, C. N. J., Watson, D. G., & Humphreys, G. W. (1999). Visual marking of locations and feature maps: Evidence from within-dimension defined conjunctions. *Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology.*, 52A(3), 679-715.
- O'Regan, J. K. (1992). Solving the "real" mysteries of visual perception: The world as an outside memory. *Canadian Journal of Psychology*, 46, 461-488.
- O'Regan, J. K., Deubel, H., Clark, J. J., & Rensink, R. A. (2000). Picture changes during blinks: looking without seeing and seeing without looking. *Visual Cognition*, 7, 191-212.
- O'Regan, J. K., & Lévy-Schoen, A. (1983). Integrating visual information from successive fixations: Does trans-saccadic fusion exist? *Vision Research*, 23(8), 765-768.
- O'Regan, J. K., & Noë, A. (2002). A sensorimotor account of vision and visual consciousness. *Behavioral and Brain Sciences*, 24(5), xxx-xxx.
- Paivio, A. (1971). *Imagery and Verbal Processes*. New York: Holt, Reinhart, and Winston.
- Paivio, A. (1986). *Mental Representations*. New York: Oxford University Press.
- Paivio, A., & te Linde, J. (1980). Symbolic comparisons of objects on color attributes. *Journal of Experimental Psychology: Human Perception & Performance*, 6(4), 652-661.
- Palmer, S. E. (1977). Hierarchical structure in perceptual representation. *Cognitive Psychology*, 9, 441-474.
- Palmer, S. E. (1978). Structural aspects of visual similarity. *Memory and Cognition*, 6, 91-97.
- Parks, T. E. (1965). Post-Retinal Visual Storage. *American Journal of Psychology*, 78, 145-147.
- Parks, T. E. (1968). Further comments on the evidence for post-retinal storage. *Perception & Psychophysics*, 4(6), 373.
- Parks, T. E. (1994). On the microgenesis of illusory figures: a failure to replicate. *Perception*, 23, 857-862.
- Parks, T. E. (1995). The microgenesis of illusory figures: evidence for visual hypothesis testing. *Perception*, 24, 681-684.
- Pashler, H. (1995). Attention and visual perception: analyzing divided attention. In S. M. Kosslyn & D. N. Osherson (Eds.), *Visual Cognition* (2nd ed., pp. 71-100). Cambridge, MA: MIT Press.
- Pashler, H. E. (1998). *The Psychology of Attention*. Cambridge, MA: MIT Press (A Bradford Book).
- Patterson, J., & Deffenbacher, K. (1972). Haptic perception of the Mueller-Lyer illusion by the blind. *Perceptual & Motor Skills*, 35(3), 819-824.
- Pavani, F., Ladavas, E., & Driver, J. (2002). Selective deficit of auditory localisation in patients with visuospatial neglect. *Neuropsychologia*, 40(3), 291-301.
- Pentland, A. P. (1986). Perceptual organization and the representation of natural form. *Artificial Intelligence*, 28, 293-331.
- Perky, C. W. (1910a). An Experimental study of imagination. *American Journal of Psychology*, 21(3), 422-452.
- Perky, C. W. (1910b). An experimental study of imagination. *American Journal of Psychology*, 21, 422-452.
- Perrett, D. I., Harries, M. H., Benson, P. J., Chitty, A. J., & Mistlin, A. J. (1990). Retrieval of structure from rigid and biological motion: An analysis of the visual responses of neurones in the Macaque temporal cortex. In A. Blake & T. Troscianko (Eds.), *AI and the Eye* (pp. 181-200). Chichester, England: John Wiley & Sons.
- Perrett, D. I., Mistlin, A. J., & Chitty, A. J. (1987). Visual neurones responsive to faces. *Trends in Neuroscience*, 10, 358-364.
- Perry, J. (1979). The problem of the essential indexical. *Noûs*, 13, 3-21.
- Pessoa, L., Thompson, E., & Noë, A. (1998). Finding out about filling in: A guide to perceptual completion for visual science and the philosophy of perception. *Behavioral and Brain Sciences*, 21(6), 723-802.
- Peterson, M. A. (1993). The ambiguity of mental images: insights regarding the structure of shape memory and its function in creativity. In H. Roskos-Ewoldson & M. J. Intons-Peterson & R. E. Anderson (Eds.), *Imagery, creativity, and discovery: A cognitive perspective. Advances in psychology, Vol. 98*. Amsterdam, Netherlands: North Holland/Elsevier Science Publishers.
- Peterson, M. A., & Gibson, B. S. (1991). Directing spatial attention within an object: Altering the functional equivalence of shape description. *Journal of Experimental Psychology: Human Perception and Performance*, 17(1), 170-182.
- Peterson, M. A., & Hochberg, J. (1983). Opposed-set measurement procedure: A quantitative analysis of the role of local cues and intention in form perception. *Journal of Experimental Psychology: Human Perception and Performance*, 9, 183-193.

- Peterson, M. A., Kihlstrom, J. F., Rose, P. M., & Glisky, M. A. (1992). Mental images can be ambiguous: Reconstruals and reference-frame reversals. *Memory and Cognition*, 20(2), 107-123.
- Piaget, J., & Inhelder. (1957). *The Child's Conception of Space*. New York: Humanities Press.
- Pinker, S. (1980). Mental imagery and the third dimension. *Journal of Experimental Psychology: General*, 109(3), 354-371.
- Pinker, S. (1994). *The Language Instinct: How the mind creates language*. New York: W. Morrow and company.
- Pinker, S. (1997). *How the mind works*. New York: Norton.
- Pinker, S., Choate, P. A., & Finke, R. A. (1984). Mental extrapolation in patterns constructed from memory. *Memory & Cognition*, 12(3), 207-218.
- Pinker, S., & Finke, R. A. (1980). Emergent two-dimensional patterns in images rotated in depth. *Journal of Experimental Psychology: Human Perception & Performance*, 6(2), 244-264.
- Planck, M. (1933). *Where is Science Going?* (J. Murphy, Trans.). London: Allen & Unwin.
- Podgorny, P., & Shepard, R. N. (1978). Functional representations common to visual perception and imagination. *Journal of Experimental Psychology: Human Perception and Performance*, 4(1), 21-35.
- Poggio, T., Torre, V., & Koch, C. (1990). Computational vision and regularization theory. In S. Ullman & W. Richards (Eds.), *Image Understanding 1989* (Vol. 3, pp. 1-18). Norwood, N.J.: Ablex Publishing.
- Pointcaré, H. (1963). Why space has three dimensions, *Mathematics and Science: Last Essays*. New York: Dover.
- Posner, M. I. (1978). *Chronometric Explorations of Mind*. Hillsdale, N.J.: Erlbaum.
- Posner, M. I. (1980). Orienting of Attention. *Quarterly Journal of Experimental Psychology*, 32, 3-25.
- Posner, M. I., Nissen, M. J., & Ogden, W. C. (1978). Attended and unattended processing modes: The role of set for spatial location. In H. L. Pick & I. J. Saltzman (Eds.), *Modes of perceiving and processing information*. Hillsdale, NJ: Erlbaum.
- Potter, M. C. (1975). Meaning in visual search. *Science*, 187(4180), 965-966.
- Predebon, J., & Wenderoth, P. (1985). Imagined stimuli: Imaginary effects? *Bulletin of the Psychonomic Society*, 23(3), 215-216.
- Proteau, L. (1992). On the specificity of learning and the role of visual information for movement control. In L. Proteau & D. Elliot (Eds.), *Vision and motor control. Advances in Psychology No. 85* (pp. 67-103). Amsterdam, Netherlands: North-Holland.
- Pylyshyn, Z. W. (1973). What the Mind's Eye Tells the Mind's Brain: A Critique of Mental Imagery. *Psychological Bulletin*, 80, 1-24.
- Pylyshyn, Z. W. (1978). Imagery and Artificial Intelligence. In C. W. Savage (Ed.), *Perception and Cognition: Issues in the Foundations of Psychology* (Vol. 9). Minneapolis: Univ. of Minnesota Press.
- Pylyshyn, Z. W. (1979a). Do Mental Events Have Durations? *Behavioral and Brain Sciences*, 2(2), 277-278.
- Pylyshyn, Z. W. (1979b). The Rate of 'Mental Rotation' of Images: A Test of a Holistic Analogue Hypothesis. *Memory and Cognition*, 7, 19-28.
- Pylyshyn, Z. W. (1979c). Validating Computational Models: A Critique of Anderson's Indeterminacy of Representation Claim. *Psychological Review*, 86(4), 383-394.
- Pylyshyn, Z. W. (1980). Cognitive Representation and the Process-Architecture Distinction. *Behavioral and Brain Sciences*, 3(1), 154-169.
- Pylyshyn, Z. W. (1981). The imagery debate: Analogue media versus tacit knowledge. *Psychological Review*, 88, 16-45.
- Pylyshyn, Z. W. (1984a). *Computation and cognition: Toward a foundation for cognitive science*. Cambridge, MA: MIT Press.
- Pylyshyn, Z. W. (1984b). Plasticity and Invariance in Cognitive Development. In J. M. a. R. Fox (Ed.), *Neonate Cognition: Beyond the Blooming, Buzzing Confusion*. Hillsdale, N.J.: Erlbaum.
- Pylyshyn, Z. W. (1989). The role of location indexes in spatial perception: A sketch of the FINST spatial-index model. *Cognition*, 32, 65-97.
- Pylyshyn, Z. W. (1991a). The role of cognitive architectures in theories of cognition. In K. VanLehn (Ed.), *Architectures for Intelligence*. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Pylyshyn, Z. W. (1991b). Rules and Representation: Chomsky and representational realism. In A. Kashir (Ed.), *The Chomskian Turn*. Oxford: Basil Blackwell Limited.
- Pylyshyn, Z. W. (1996). The study of cognitive architecture. In D. Steier & T. Mitchell (Eds.), *Mind Matters: Contributions to Cognitive Science in honor of Allen Newell*. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Pylyshyn, Z. W. (1998). Visual indexes in spatial vision and imagery. In R. D. Wright (Ed.), *Visual Attention* (pp. 215-231). New York: Oxford University Press.

- Pylyshyn, Z. W. (1999). Is vision continuous with cognition? The case for cognitive impenetrability of visual perception. *Behavioral and Brain Sciences*, 22(3), 341-423.
- Pylyshyn, Z. W. (2000). Situating vision in the world. *Trends in Cognitive Sciences*, 4(5), 197-207.
- Pylyshyn, Z. W. (2001a). Connecting vision and the world: Tracking the missing link. In J. Branquinho (Ed.), *The Foundations of Cognitive Science* (pp. 183-195). Oxford, UK: Clarendon Press.
- Pylyshyn, Z. W. (2001b). Visual indexes, preconceptual objects, and situated vision. *Cognition*, 80(1/2), 127-158.
- Pylyshyn, Z. W. (2002). Mental Imagery: In search of a theory. *Behavioral and Brain Sciences*, 25(2), xxx-xxx.
- Pylyshyn, Z. W. (Ed.). (1987). *The Robot's Dilemma: The Frame Problem in Artificial Intelligence*. Norwood, NJ: Ablex Publishing.
- Pylyshyn, Z. W., Burkell, J., Fisher, B., Sears, C., Schmidt, W., & Trick, L. (1994). Multiple parallel access in visual attention. *Canadian Journal of Experimental Psychology*, 48(2), 260-283.
- Pylyshyn, Z. W., & Cohen, J. (1999). *Imagined extrapolation of uniform motion is not continuous*. Paper presented at the Annual Conference of the Association for Research in Vision and Ophthalmology, May 1999., Ft. Lauderdale, FL.
- Pylyshyn, Z. W., & Eagleson, R. A. (1994). Developing a network model of multiple visual indexing (abstract). *Investigative Ophthalmology and Visual Science*, 35(4), 2007-2007.
- Pylyshyn, Z. W., Elcock, E. W., Marmor, M., & Sander, P. (1978). *Explorations in visual-motor spaces*. Paper presented at the Proceedings of the Second International Conference of the Canadian Society for Computational Studies of Intelligence, University of Toronto.
- Pylyshyn, Z. W., & Storm, R. W. (1988). Tracking multiple independent targets: evidence for a parallel tracking mechanism. *Spatial Vision*, 3(3), 1-19.
- Radeau, M. (1994). Auditory-visual spatial interaction and modularity. *Cahiers de Psychologie Cognitive / Current Psychology of Cognition*, 13(1), 3-51.
- Rafal, R. D. (1997). Balint syndrome. In T. Feinberg & M. Farah (Eds.), *Behavioral neurology and neuropsychology* (pp. 337-356). New York: McGraw-Hill.
- Rafal, R. D. (1998). Neglect. In R. Parasurman (Ed.), *The Attentive Brain* (pp. 489-525). Cambridge, MA: MIT Press.
- Ramachandran, V. S. (1976). Learning-like phenomena in stereopsis. *Nature*, 262(5567), 382-384.
- Ramachandran, V. S., & Braddick, O. (1973). Orientation specific learning in stereopsis. *Perception*, 2, 371-376.
- Ranney, M. (1989). Internally represented forces may be cognitively penetrable: Comment on Freyd, Pantzer, and Cheng (1988). *Journal of Experimental Psychology: General*, 118(4), 399-402.
- Reddy, D. R. (Ed.). (1975). *Speech Recognition*. New York: Academic Press.
- Reed, S. K., Hock, H. S., & Lockhead, G. R. (1983). Tacit knowledge and the effect of pattern configuration on mental scanning. *Memory and Cognition*, 11, 137-143.
- Reisberg, D., & Chambers, D. (1991). Neither pictures nor propositions: What can we learn from a mental image? *Canadian Journal of Psychology*, 45(3), 336-352.
- Reisberg, D., & Morris, A. (1985). Images contain what the imager put there: A nonreplication of illusions in imagery. *Bulletin of the Psychonomic Society*, 23(6), 493-496.
- Rensink, R. A. (2000). The dynamic representation of scenes. *Visual Cognition*, 7, 17-42.
- Rensink, R. A., O'Regan, J. K., & Clark, J. J. (1997). To see or not to see: The need for attention to perceive changes in scenes. *Psychological Science*, 8(5), 368-373.
- Rensink, R. A., O'Regan, J. K., & Clark, J. J. (2000). On the failure to detect changes in scenes across brief interruptions. *Visual Cognition*, 7, 127-145.
- Reynolds, R. (1981). Perception of an illusory contour as a function of processing time. *Perception*, 10, 107-115.
- Reynolds, R. I. (1978). The microgenetic development of the Ponzo and Zollner illusions. *Perception and Psychophysics*, 23, 231-236.
- Reynolds, R. I. (1985). The role of object-hypotheses in the organization of fragmented figures. *Perception*, 14, 49-52.
- Richards, W. (1980, April 25-27, 1979). *Natural computation: Filing a perceptual void*. Paper presented at the The 10th Annual Conference on Modelling and Simulation, University of Pittsburgh.
- Richards, W. (Ed.). (1988). *Natural Computation*. Cambridge, MA: MIT Press (A Bradford Book).
- Richman, C. L., Mitchell, D. B., & Reznick, J. S. (1979). Mental travel: Some reservations. *Journal of Experimental Psychology: Human Perception and Performance*, 5, 13-18.

- Richter, W., Somorjai, R., Summers, R., Jarmasz, M., Menon, R. S., Gati, J. S., Georgopoulos, A. P., Tegeler, C., Ugurbil, K., & Kim, S.-G. (2000). Motor area activity during mental rotation studied by time-resolved single-trial fMRI. *Journal of Cognitive Neuroscience*, *12*(2), 310-320.
- Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 1157-1165.
- Rieser, J. J., Guth, D. A., & Hill, E. W. (1986). Sensitivity to perspective structure while walking without vision. *Perception*, *15*, 173-188.
- Riseman, E. M., & Hanson, A. R. (1987). A methodology for the development of general knowledge-based vision systems. In M. A. Arbib & A. R. Hanson (Eds.), *Vision, Brain, and Cooperative Computation*. Cambridge, MA: MIT Press (A Bradford Book).
- Roberts, L. G. (1965). Machine perception of three-dimensional solids. In J. P. Tippett (Ed.), *Optical and electro-optical information processing*. Cambridge, MA: MIT Press.
- Rock, I. (1973). *Orientation and Form*. New York: Academic Press.
- Rock, I. (1981). Anorthoscopic perception. *Scientific American*, *224*(2), 145-153.
- Rock, I. (1983). *The Logic of Perception*. Cambridge, Mass.: MIT Press, a Bradford Book.
- Rock, I. (Ed.). (1997). *Indirect Perception*. Cambridge, MA: MIT Press.
- Rock, I., & Anson, R. (1979). Illusory contours as the solution to a problem. *Perception*, *8*, 655-681.
- Rock, I., & Gutman, D. (1981). The effect of inattention on form perception. *Journal of Experimental Psychology: Human Perception and Performance*, *7*, 275-285.
- Rode, G., Rossetti, Y., & Bission, D. (2001). Prism adaptation improves representational neglect. *Neuropsychologia*, *39*(11), 1250-1254.
- Roland, P. E., & Gulyas, B. (1994a). Beyond 'pet' methodologies to converging evidence: Reply. *Trends in Neurosciences*, *17*(12), 515-516.
- Roland, P. E., & Gulyas, B. (1994b). Visual imagery and visual representation. *Trends in Neurosciences*, *17*(7), 281-287.
- Roland, P. E., & Gulyas, B. (1995). Visual memory, visual imagery, and visual recognition of large field patterns by the human brain: Functional anatomy by positron emission tomography. *Cerebral Cortex*, *5*(1), 79-93.
- Rosch, E. H., Mervis, C. B., Gray, W. D., Johnson, D. M., & Boyes-Braem, P. (1976). Basic objects in natural categories. *Cognitive Psychology*, *8*, 382-439.
- Rosenblatt, F. (1959). Two theorems of statistical separability in the perceptron, *National Physical Laboratory, Symposium on Mechanization of Thought Processes*. London: HM Stationery Office.
- Rosenfeld, A., Hummel, R. A., & Zucker, S. W. (1976). Scene labeling by relaxation operators. *IEEE Transactions on Systems, Man, and Cybernetics*, *SMC-6*, 420-433.
- Russell, B. (1918/1985). The Philosophy of Logical Atomism. In D. F. Pears (Ed.), *The Philosophy of Logical Atomism* (pp. 35-155). Lasalle: Open Court.
- Sagi, D., & Julesz, B. (1984). Detection versus discrimination of visual orientation. *Perception*, *13*, 619-628.
- Samson, D., Pillon, A., & De Wilde, V. (1998). Impaired knowledge of visual and non-visual attributes in a patient with a semantic impairment for living entities: A case of a true category-specific deficit. *Neurocase: Case Studies in Neuropsychology, Neuropsychiatry, & Behavioural Neurology*, *4*(4-5), 273-290.
- Samuel, A. G. (1981). Phonemic restoration: Insights from a new methodology. *Journal of Experimental Psychology: General*, *110*(4), 474-494.
- Sarter, M., Berntson, G. G., & Cacioppo, J. T. (1996). Brain imaging and cognitive neuroscience: Toward strong inference in attributing function to structure. *American Psychologist*, *51*(1), 13-21.
- Saye, A., & Frisby, J. P. (1975). The role of monocularly conspicuous features in facilitating stereopsis from random-dot stereograms. *Perception*, *4*(2), 159-171.
- Schlingensiepen, K. H., Campbell, F. W., Legge, G. E., & Walker, T. D. (1986). The importance of eye movements in the analysis of simple patterns. *Vision Research*, *26*(7), 1111-1117.
- Schmidt, W. C., Fisher, B. D., & Pylyshyn, Z. W. (1998). Multiple-location access in vision: Evidence from illusory line motion. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(2), 505-525.
- Scholl, B. J., & Pylyshyn, Z. W. (1999). Tracking multiple items through occlusion: Clues to visual objecthood. *Cognitive Psychology*, *38*(2), 259-290.
- Scholl, B. J., Pylyshyn, Z. W., & Feldman, J. (2001). What is a visual object: Evidence from target-merging in multiple-object tracking. *Cognition*, *80*, 159-177.
- Schulz, T. (1991). A microgenetic study of the Mueller-Lyer illusion. *Perception*, *20*(4), 501-512.

- Schweinberger, S. R., & Stief, V. (2001). Implicit perception in patients with visual neglect: Lexical specificity in repetition priming. *Neuropsychologia*, *39*(4), 420-429.
- Schyns, Goldstone, & Thibaut. (1998). The development of features in object concepts. *Behavioral and Brain Sciences*, *21*, 1-54.
- Searle, J. R. (1990). Consciousness, explanatory inversion, and cognitive science. *Behavioral & Brain Sciences*, *13*(4), 585-642.
- Searle, J. R. (1995). The problem of consciousness. In J. King & K. H. Pribram (Eds.), *Scale in conscious experience: Is the brain too important to be left to specialists to study?* (pp. 13-22). Mahwah, NJ, USA: Lawrence Erlbaum Associates, Inc.
- Sears, C. (1996). *Visual Indexing and Inhibition of Return of Visual Attention*. Unpublished PhD, University of Western Ontario, London, Canada.
- Sears, C. R., & Pylyshyn, Z. W. (2000). Multiple object tracking and attentional processes. *Canadian Journal of Experimental Psychology*, *54*(1), 1-14.
- Segal, S. J., & Fusella, V. (1969). Effects of imaging on signal-to-noise ratio, with varying signal conditions. *British Journal of Psychology*, *60*(4), 459-464.
- Segal, S. J., & Fusella, V. (1970). Influence of imaged pictures and sounds on detection of visual and auditory signals. *Journal of Experimental Psychology*, *83*(3), 458-464.
- Sekuler, A. B., & Palmer, S. E. (1992). Visual completion of partly occluded objects: A microgenetic analysis. *Journal of Experimental Psychology: General*, *121*, 95-111.
- Sekuler, R., & Blake, R. (1994). *Perception* (Second ed.). New York: McGraw-Hill.
- Selfridge, O. (1959). Pandemonium: A paradigm for learning, *Symposium on Mechanization of Thought Processes: National Physical Laboratory Symposium*. London: HM Stationery Office.
- Sergent, J. (1994). Brain-imaging studies of cognitive functions. *Trends in Neurosciences*, *17*, 221-227.
- Servos, P., & Goodale, M. A. (1995). Preserved visual imagery in visual form agnosia. *Neuropsychologia*(Nov), 1383-1394.
- Shapiro, K. L., & Raymond, J. E. (1989). Training of efficient oculomotor strategies enhances skill acquisition. *Acta Psychologica*, *71*(1-3), 217-242.
- Sheingold, K., & Tenney, Y. J. (1982). Memory for a salient childhood event. In U. Neisser (Ed.), *Memory Observed* (pp. 201-212). San Francisco, CA: W.H. Freeman and Co.
- Shepard, R. N. (1978a). Externalization of mental images and the act of creation. In B. S. Randhawa & W. E. Coffman (Eds.), *Visual Learning, Thinking and Communication* (pp. 133-189). New York: Academic Press.
- Shepard, R. N. (1978b). The Mental Image. *American Psychologist*, *33*, 125-137.
- Shepard, R. N. (1981). Psychophysical complementarity. In M. Kubovy & J. R. Pomerantz (Eds.), *Perceptual Organization* (pp. 279-342). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Shepard, R. N., & Chipman, S. (1970). Second-Order Isomorphism of Internal Representations: Shapes of States. *Cognitive Psychology*, *1*, 1-17.
- Shepard, R. N., & Feng, C. (1972). A Chronometric Study of Mental Paper Folding. *Cognitive Psychology*, *3*, 228-243.
- Shepard, R. N., & Metzler, J. (1971). Mental rotation of three dimensional objects. *Science*, *171*, 701-703.
- Shepherd, M., & Mueller, H. J. (1989). Movement versus focusing of visual attention. *Perception & Psychophysics*, *46*(2), 146-154.
- Shiffrin, R. M., & Nosofsky, R. M. (1994). Seven plus or minus two: A commentary on capacity limitations. *Psychological Review*, *101*(2), 357-361.
- Shirai, Y. (1975). Analyzing intensity arrays using knowledge about scenes. In P. H. Winston (Ed.), *Psychology of Computer Vision*. Cambridge, MA: MIT Press.
- Shulman, G. L., Remington, R. W., & McLean, J. P. (1979). Moving attention through visual space. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 522-526.
- Shulman, G. L., & Wilson, J. (1987). Spatial frequency and selective attention to local and global information. *Perception*, *16*(1), 89-101.
- Shuren, J. E., Brott, T. G., Schefft, B. K., & Houston, W. (1996). Preserved color imagery in an achromatopsic. *Neuropsychologia*, *34*(6), 485-489.
- Sigman, E., & Rock, I. (1974). Stroboscopic movement based on perceptual intelligence. *Perception*, *3*(1), 9-28.
- Silbersweig, D. A., & Stern, E. (1998). Towards a functional neuroanatomy of conscious perception and its modulation by volition: implications of human auditory neuroimaging studies. *Philos Trans R Soc Lond B Biol Sci*, *353*(1377), 1883-1888.

- Sillito, A. M., Jones, H. E., Gerstein, G. L., & West, D. C. (1994). Feature-linked synchronization of thalamic relay cell firing induced by feedback from the visual cortex. *Nature*, 369(6480), 479-482.
- Simon, H. A. (1969). *The Sciences of the Artificial*. Cambridge, Mass.: MIT Press.
- Simon, H. A. (1975). The functional equivalence of problem solving skills. *Cognitive Psychology*, 7, 268-288.
- Simon, T. J., Hespos, S. J., & Rochat, P. (1995). Do infants understand simple arithmetic? A replication of Wynn (1992). *Cognitive Development*, 10(2), 253-269.
- Simon, T. J., & Vaishnavi, S. (1996). Subitizing and counting depend on different attentional mechanisms: Evidence from visual enumeration in afterimages. *Perception and Psychophysics*, 58(6), 915-926.
- Simons, D. J. (1996). In sight, out of mind: When object representations fail. *Psychological Science*, 7(5), 301-305.
- Simons, D. J., & Levin, D. T. (1997). Change blindness. *Trends in Cognitive Sciences*, 1, 261-267.
- Slemmer, J. A., & Johson, S. P. (2002). *Object tracking in ecologically valid occulsion events*. Paper presented at the Vision Sciences 2002, Sarasota, FL.
- Slezak, P. (1991). *Can images be rotated and inspected? A test of the pictorial medium theory*. Paper presented at the Thirteenth Annual meeting of the Cognitive Science Society.
- Slezak, P. (1992). *When can images be reinterpreted: Non-chronometric tests of pictorialism*. Paper presented at the Fourteenth Conference of the Cognitive Science Society.
- Slezak, P. (1995). The 'philosophical' case against visual imagery. In P. Slezak & T. Caelli & R. Clark (Eds.), *Perspective on Cognitive Science: Theories, Experiments and Foundations* (pp. 237-271). Stamford, CT: Ablex.
- Slezak, P. (submitted). *The Tripartite model of representation* (submitted). Sydney, Australia: Program in Cognitive Science, University of New South Wales.
- Slovan, A. (1971). Interactions between philosophy and artificial intelligence: The role of intuition and non-logical reasoning in intelligence. *Artificial Intelligence*, 2, 209-225.
- Snodgrass, J. G., & Feenan, K. (1990). Priming effects in picture fragment completion: Support for the perceptual closure hypothesis. *Journal of Experimental Psychology: General*, 119(3), 276-296.
- Soloman, R. L., & Postman, L. (1952). Frequency of usage as a determinant of recognition thresholds for words. *Journal of Experimental Psychology*, 43, 195-201.
- Spelke, E., Guthheil, G., & Van de Walle, G. (1995). The development of object perception. In S. M. Kosslyn & D. N. Osherson (Eds.), *Visual Cognition* (second ed., Vol. 2, pp. 297-330). Cambridge, MA: MIT Press.
- Spelke, E. S. (1990). Principles of object perception. *Cognitive Science*, 14, 29-56.
- Sperber, D., & Wilson, D. (1998). The mapping between the mental and the public lexicon. In P. Carruthers & J. Boucher (Eds.), *Thought and Language* (pp. 184-200). Cambridge, UK: Cambridge University Press.
- Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs*, 74 (whole No. 11).
- Sperling, G., & Melchner, M. J. (1978). The attention operating characteristic: examples from visual search. *Science*, 202(4365), 315-318.
- Sperling, G., & Weichselgarter, E. (1995). Episodic theory of the dynamics of spatial attention. *Psychological Review*, 102(3), 503-532.
- Squire, L. R., & Slater, P. C. (1975). Forgetting in very long-term memory as assessed by an improved questionnaire technique. *Journal of Experimental Psychology: Human Perception and Performance*, 104, 50-54.
- Starkes, J., Allard, F., Lindley, S., & O'Reilly, K. (1994). Abilities and skill in basketball. Special issue: expert-novice differences in sport. *International Journal of Sport Psychology*, 25(3), 249-265.
- Steinbach, M. J. (1976). Pursuing the perceptual rather than the retinal stimulus. *Vision research*, 16, 1371-1376.
- Sternberg, S. (1969). The Discovery of Processing Stages: Extensions of Donders' Method. *Acta Psychologica*, 30, 276-315.
- Stevens, J. K., Emerson, R. C., Gerstein, G. L., Kallos, T., Neufield, G. R., Nichols, C. W., & Rosenquist, A. C. (1976). Paralysis of the awake human: Visual perceptions. *Vision Research*, 16, 93-98.
- Stich, S. (1978). Beliefs and subdoxastic states. *Philosophy of Science*, 45, 499-518.
- Stoerig, P. (1996). Varieties of vision: From blind responses to conscious recognition. *Trends in Neurosciences*, 19(9), 401-406.
- Street, R. F. (1931). *A Gestalt Completion Test: A study of a cross section of intellect*. New York: Bureau of Publications, Teachers College, Columbia University.
- Stromeyer, C. F., & Psotka, J. (1970). The detailed texture of eidetic images. *Nature*, 225(230), 346-349.

- Suchman, L. A. (1987). *Plans and situated actions: The problem of human-machine communication*. Cambridge, England UK: Cambridge University Press.
- Suganuma, M., & Yokosawa, K. (2002). *Is multiple object tracking affected by three-dimensional rigidity?* Paper presented at the Vision Sciences Society, Sarasota, FL.
- Suppes, P. (1995). Some foundational problems in the theory of visual space. In R. D. Luce & M. e. a. D'Zmura (Eds.), *Geometric representations of perceptual phenomena: Papers in honor of Tarow Indow on his 70th birthday* (pp. 37-45). Mahwah, NJ: Lawrence Erlbaum Associates.
- Swinney, D. A. (1979). Lexical access during sentence comprehension: (Re)consideration of context effects. *Journal of Verbal Learning & Verbal Behavior*, *18*(6), 645-659.
- Talmy, L. (2000). *Toward a cognitive semantics, Vol. 1: Concept structuring systems*: Cambridge, MA, US: The MIT Press. (2000). viii, 565pp.
- Tanner, W. P., & Swets, J. A. (1954). A decision-making theory of human detection. *Psychological Review*, *61*, 401-409.
- Theeuwes, J., A.F., K., & Atchley, P. (1998). Visual marking of old objects. *Psychonomic Bulletin and Review*, *5*(1), 130-134.
- Thomas, N. J. T. (1999). Are theories of imagery theories of imagination? Active perception approach to conscious mental content. *Cognitive Science*, *23*(2), 207-245.
- Tipper, S., Driver, J., & Weaver, B. (1991). Object-centered inhibition of return of visual attention. *Quarterly Journal of Experimental Psychology*, *43A*, 289-298.
- Tipper, S. P., & Behrmann, M. (1996). Object-centered not scene-based visual neglect. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(5), 1261-1278.
- Tipper, S. P., Weaver, B., Jerreat, L. M., & Burak, A. L. (1994). Object-based and environment-based inhibition of return of selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(478-499).
- Titchener, E. B. (1915). *A Beginner's Psychology*. New York: Macmillan.
- Tlauka, M., & McKenna, F. P. (1998). Mental imagery yields stimulus-response compatibility. *Acta Psychologica*, *67-79*.
- Todd, J. T., Tittle, J. S., & Norman, J. F. (1995). Distortions of three-dimensional space in the perceptual analysis of motion and stereo. *Perception*, *24*(1), 75-86.
- Tootell, R. B., Silverman, M. S., Switkes, E., & de Valois, R. L. (1982). Deoxyglucose analysis of retinotopic organization in primate striate cortex. *Science*, *218*(4575), 902-904.
- Treisman, A., & DeSchepper, B. (1995). Object Tokens, Attention, and Visual Memory. In T. Inui & J. McClelland (Eds.), *Attention and Performance XVI: Information Integration in Perception and Communication* (pp. 15-46). Cambridge, MA: MIT Press.
- Treisman, A., & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology*, *12*, 97-136.
- Treisman, A., & Schmidt, H. (1982). Illusory Conjunctions in the Perception of Objects. *Cognitive Psychology*, *14*(1), 107-141.
- Treisman, A. M. (1964). Verbal cues, language and meaning in selective attention. *American Journal of Psychology*, *77*, 206-219.
- Treisman, A. M. (1969). Strategies and models of selective attention. *Psychological Review*, *76*, 282-299.
- Tremoulet, P. D., Leslie, A. M., & Hall, D. G. (2001). Infant individuation and identification of objects. *Cognitive Development*, *15*(4), 499-522.
- Trick, L., & Pylyshyn, Z. W. (1993). What enumeration studies tell us about spatial attention: Evidence for limited capacity preattentive processing. *Journal of Experimental Psychology: Human Perception and Performance*, *19*(2), 331-351.
- Trick, L. M., & Pylyshyn, Z. W. (1994a). Cuing and counting: Does the position of the attentional focus affect enumeration? *Visual Cognition*, *1*(1), 67-100.
- Trick, L. M., & Pylyshyn, Z. W. (1994b). Why are small and large numbers enumerated differently? A limited capacity preattentive stage in vision. *Psychological Review*, *101*(1), 80-102.
- Trojano, L., & Grossi, D. (1994). A critical review of mental imagery defects. *Brain & Cognition*, *24*(2), 213-243.
- Tsal, Y. (1983). Movements of attention across the visual field. *Journal of Experimental Psychology: Human Perception and Performance*, *9*, 523-530.

- Tsotsos, J. K. (1988). How does human vision beat the computational complexity of visual perception. In Z. W. Pylyshyn (Ed.), *Computational Processes in Human Vision: An interdisciplinary perspective* (pp. 286-340). Norwood, NJ: Ablex Publishing.
- Tufte, E. R. (1990). *Envisioning Information*. Cheshire, CT: Graphics Press.
- Tye, M. (1991). *The Imagery Debate*. Cambridge, MA: MIT Press.
- Uhlarik, J. J. (1973). Role of cognitive factors on adaptation to prismatic displacement. *Journal of Experimental psychology*, 98, 223-232.
- Ullman, S. (1976). On Visual Detection of Light Sources. *Biological Cybernetics*, 21, 205-212.
- Ullman, S. (1979). *The interpretation of visual motion*. Cambridge, MA: MIT Press.
- Ullman, S. (1984). Visual routines. *Cognition*, 18, 97-159.
- Ullman, S., & Richards, W. (Eds.). (1990). *Image Understanding* (Vol. 4). Norwood, NJ: Ablex Publishers.
- Ungerleider, L. G., & Mishkin, M. (1982). Two cortical visual systems. In J. Ingle & M. A. Goodale & R. J. W. Mansfield (Eds.), *Analysis of visual behavior* (pp. 549-586). Cambridge, MA: MIT Press.
- Uttal, w. (1967). Evoked Brain Potentials: Signs or Codes? *Perspectives in Biology and Medicine*, 10, 627-639.
- Uttley, A. M. (1959). Conditional Probability Computing in the nervous system, *National Physical Laboratory, Symposium on Mechanization of Thought Processes* (Vol. 1, pp. 119-149). London: HM Stationery Office.
- Van der Heijden, A. H., Schreuder, R., & Wolters, G. (1985). Enhancing single-item recognition accuracy by cueing spatial locations in vision. *Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, 37A(3), 427-434.
- van Essen, D. C., & Anderson, C. H. (1990). Information processing strategies and pathways in the primate retina and visual cortex. In S. F. Zornetzer & J. L. Davis & C. Lau (Eds.), *Introduction to Neural and Electronic Networks*. New York: Academic Press.
- VanLehn, K., & Ball, W. (1991). Goal reconstruction: How TETON blends situated action and planned action. In K. VanLehn (Ed.), *Architectures for Intelligence* (pp. 147-188). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Virsu, V. (1971). Tendencies to eye movement, and misperception of curvature, direction, and length. *Perception & Psychophysics*, 9(1-B), 65-72.
- Viswanathan, L., & Mingolla, E. (submitted). Dynamics of attention in depth: Evidence from multi-element tracking.
- von Holst, E., & Mittelstaedt, H. (1971/1950). The principle of reafference: Interactions between the central nervous system and the peripheral organs. In P. C. Dodwell (Ed.), *Perceptual processing: Stimulus equivalence and pattern recognition* (pp. 41-71). New York: Appleton.
- Vuilleumier, P., & Rafal, R. (1999). "Both" means more than "two": Localizing and counting in patients with visuospatial neglect. *Nature Neuroscience*, 2(9), 783-784.
- Wallace, B. (1984a). Apparent equivalence between perception and imagery in the production of various visual illusions. *Memory & Cognition*, 12(2), 156-162.
- Wallace, B. (1984b). Creation of the horizontal-vertical illusion through imagery. *Bulletin of the Psychonomic Society*, 22(1), 9-11.
- Wallace, B. (1991). Imaging ability and performance in a proofreading task. *Journal of Mental Imagery*, 15(3-4), 177-188.
- Wallach, H. (1976). *On perception*. New York: Quadrangle/New York Times Book Co.
- Wallach, H., & O'Connell, D. N. (1953). The kinetic depth effect. *Journal of Experimental Psychology*, 45, 205-217.
- Waltz, D. (1975). Understanding Line Drawings of Scenes with Shadows. In P. H. Winston (Ed.), *The Psychology of Computer Vision* (pp. 19-91). New York: McGraw-Hill.
- Ward, R., Goodrich, S., & Driver, J. (1994). Grouping reduces visual extinction: Neuropsychological evidence for weight-linkage in visual selection. *Visual Cognition*, 1, 101-129.
- Watanabe, K., & Shimojo, S. (1998). Attentional modulation in perception of visual motion events. *Perception*, 27(9), 1041-1054.
- Watson, D. G., & Humphreys, G. W. (1997). Visual marking: prioritizing selection for new objects by top-down attentional inhibition of old objects. *Psychological Review*, 104(1), 90-122.
- Watson, D. G., & Humphreys, G. W. (1998). Visual marking of moving objects: A role for top-down feature-based inhibition in selection. *Journal of Experimental Psychology: Human Perception and Performance*, 24(3), 946-962.
- Weinstein, E. L. (1974). *The influence of symbolic systems on perspective drawings: A developmental approach*. Unpublished M.Sc. Thesis, University of Toronto, Toronto, Canada.

- Weiskrantz, L. (1995). Blindsight: Not an island unto itself. *Current Directions in Psychological Science*, 4(5), 146-151.
- Weiskrantz, L. (1997). *Consciousness lost and found: A neuropsychological exploration*. New York, NY, US: Oxford University Press.
- Weiskrantz, L., Warrington, E., Sanders, M. D., & Marshall, J. (1974). Visual capacity in the hemianopic field following restricted occipital ablation. *Brain*, 97, 709-729.
- Wexler, M., Kosslyn, S. M., & Berthoz, A. (1998). Motor processes in mental rotation. *Cognition*, 68(1), 77-94.
- Wiggins, D. (1979). *Sameness and Substance*. London: UK: Blackwell.
- Wilson, J. A., & Robinson, J. O. (1986). The impossibly-twisted Pulfrich pendulum. *Perception*, 15(4), 503-504.
- Winston, P. H. (1974). *New progress in artificial intelligence* (MIT-AI-74-310). Cambridge, MA: MIT Artificial Intelligence Laboratory.
- Winston, P. H. (1984). *Artificial Intelligence (second edition)*. Reading, MA: Addison-Wesley.
- Wittgenstein, L. (1953). *Philosophical Investigations [Philosophische Untersuchungen]*. Oxford: Blackwell.
- Wittrich, W. J. (1959). Visual perception and personality. *Scientific American*, 200 (April), 56-75.
- Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided search: an alternative to the feature integration model for visual search. *J Experimental Psychology: Human Perception and Performance*, 15(3), 419-433.
- Wong, E., & Mack, A. (1981). Saccadic programming and perceived location. *Acta Psychologica*, 48, 123-131.
- Woods, W. A. (1978). Theory Formation and Control in a Speech Understanding System with Extrapolations towards Vision, *Computer Vision Systems: Papers from the workshop on computer vision systems*. New York: Academic Press.
- Wright, R. D., & Richard, C. M. (1995). *Subitizing abrupt-onset visual stimuli*. Paper presented at the Annual meeting of the Canadian Society for Brain, Behavior and Cognitive Science, Halifax, Nova Scotia.
- Wright, R. D., & Richard, C. M. (1996). Inhibition-of-return at multiple locations in visual space. *Canadian Journal of Experimental Psychology*, 50(3), 324-327.
- Wyatt, H. J., & Pola, J. (1979). The role of perceived motion in smooth pursuit eye movements. *Vision Research*, 19, 613-618.
- Wynn, K. (1992). Addition and subtraction by human infants. *Nature*, 358, 749-750.
- Wynn, K. (1998). Psychological foundations of number: Numerical understanding in human infants. *Trends in Cognitive Sciences*, 2, 296-303.
- Xu, F. (1997). From Lot's wife to a pillar of salt: Evidence that *physical object* is a sortal concept. *Mind and language*, 12, 365-392.
- Xu, F., & Carey, S. (1996). Infants' Metaphysics: The case of numerical identity. *Cognitive Psychology*, 30, 111-153.
- Yantis, S. (1992). Multielement visual tracking: Attention and perceptual organization. *Cognitive Psychology*, 24, 295-340.
- Yantis, S. (1995). Perceived continuity of occluded visual objects. *Psychological Science*, 6(3), 182-186.
- Yantis, S. (1998). Objects, Attention, and Perceptual Experience. In R. Wright (Ed.), *Visual Attention* (pp. 187-214). Oxford, GB: Oxford University Press.
- Yantis, S., & Gibson, B. S. (1994). Object continuity in apparent motion and attention. *Canadian Journal of Experimental Psychology*, 48(2), 182-204.
- Yantis, S., & Jones, E. (1991). Mechanisms of attentional selection: temporally modulated priority tags. *Perception and Psychophysics*, 50(2), 166-178.
- Zhou, H., & May, J. G. (1993). Effects of spatial filtering and lack of effects of visual imagery on pattern-contingent color aftereffects. *Perception and Psychophysics*, 53, 145-149.
- Zimler, J., & Keenan, J. M. (1983). Imagery in the congenitally blind: How visual are visual images? *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 9(2), 269-282.
- Zucker, S. W., Rosenfeld, A., & David, L. S. (1975). *General purpose models: Expectations about the unexpected*. Paper presented at the Fourth International Joint Conference on Artificial Intelligence, Tbilisi, Georgia, USSR.