

## The Interpolation of Object and Surface Structure

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One of the main theoretical challenges of vision science is to explain how the visual system interpolates missing structure. Two forms of visual completion have been distinguished on the basis of the phenomenological states that they induce. *Modal* completion refers to the formation of visible surfaces and/or contours in image regions where these properties are not specified locally. *Amodal* completion refers to the perceived unity of objects that are partially obscured by occluding surfaces. Although these two forms of completion elicit very different phenomenological states, it has been argued that a common mechanism underlies modal and amodal boundary and surface interpolation (the “identity hypothesis”; Kellman & Shipley, 1991; Kellman, 2001). Here, we provide new data, demonstrations, and theoretical principles that challenge this view. We show that modal boundary and surface completion processes exhibit a strong dependence on the prevailing luminance relationships of a scene, whereas amodal completion processes do not. We also demonstrate that the shape of interpolated contours can change when a figure undergoes a transition from a modal to an amodal appearance, in direct contrast to the identity hypothesis. We argue that these and previous results demonstrate that modal and amodal completion do not result from a common interpolation mechanism. © 2002 Elsevier Science (USA)

*Key Words:* form and shape perception; illusory contours; depth; object perception; grouping.

### INTRODUCTION

One of the fundamental problems of vision science is understanding how the visual system recovers object and surface structure from the images on the retinae. It is now well known that the visual system contains mechanisms that go beyond the information present in the two eyes by actively connecting image regions that are physically disconnected on the retinae. This process is generally known as *visual completion*.

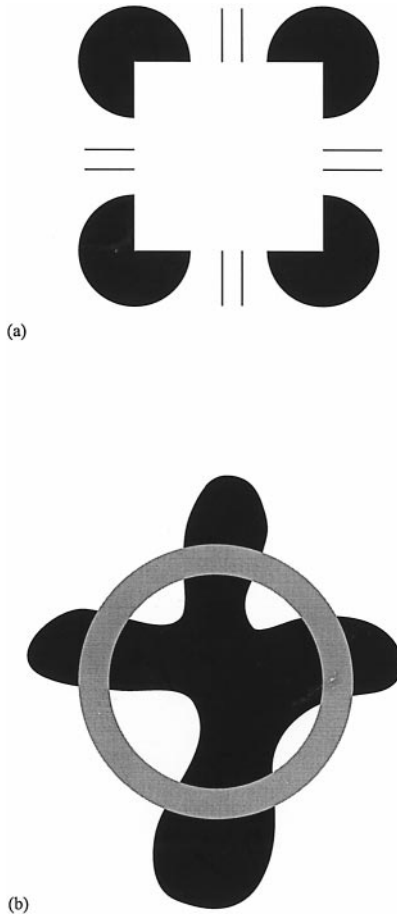
Two broad classes of visual completion have been distinguished on the basis of the phenomenological states that they induce. In some cases, comple-

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tion leads to a clear visual impression of a contour or surface in locations where there is no local image contrast to support this percept. This class of visual completion is known as *modal* completion (Michotte, Thines, & Crabbe, 1964) because the interpolated structure generates the same visual “modes” as real image contrast. Probably the most well-known example of this type of completion are the illusory figures introduced by Kanizsa (Fig. 1a). By contrast, there are other cases in which visual completion does not lead to any immediate sensation of a contour or surface. Rather, distant image fragments appear to form a single coherent object behind occluding surfaces, but without generating any visually experienced structure (local contrast) in the interpolated region. An example of this form of completion can be seen in Fig. 1b. In this figure, observers report the impression of a single, relatively distant object continuing behind a nearer, occluding object, although no perceptible structure (contrast) is experienced in the image regions in which this interpolation occurs. Because the impression of unity in these figures does not generate the same visual “modes” as a visible contour or surface, this type of completion has been called *amodal*.

Despite these differences in subjective experience, both modal and amodal completion involve the connection of disjoint image fragments into a coherent representation of objects, surfaces, and contours. This suggests the possibility that a common mechanism (or mechanisms) may underlie both forms of completion. In an influential series of studies, Kellman, Shipley, and colleagues have argued just this (Kellman & Shipley, 1991; Shipley & Kellman, 1992; Kellman, Yin, & Shipley, 1998). Specifically, these authors have argued that the phenomenal differences between modal and amodal percepts are not due to a difference in the *interpolation* mechanisms responsible for the completion. Rather, Kellman and Shipley have asserted that an identical mechanism underlies both modal and amodal completion, an assertion that they have dubbed the *identity hypothesis*. In this account, differences in the appearance of modally and amodally completed figures arise from the depth placement of completed contours and surfaces. In this theory, the placement of completed contours and surfaces in depth is assumed to be separable from the processes performing the completion. Although this theory remains mute on *how* depth differences ultimately give rise to phenomenological distinct states, the main tenet of the identity hypothesis is that these phenomenological differences do not reflect the operation of different completion mechanisms.

Thus, Kellman and Shipley (1991) have asserted that “the process of locating units in depth is separable from the process of unit formation” (Kellman & Shipley, 1991, p. 162). Despite the rather widespread acceptance of this view, in this article we argue that “unit formation” and the localization of units in depth *cannot* be separated as these authors have suggested and that the identity hypothesis is therefore incorrect. In order to assess this claim, we must consider the possible meanings of the terms “units” and “unit



**FIG. 1.** Two displays illustrating the difference between modal and amodal completion. Panel a is typically perceived as a continuous white square lying on top of four black disks against a white background. Because the square is the same color as the background surrounding the disks, there are locations where the square does not contribute any contrast to the image. The visual system interpolates the representation of the near surface across these gaps in the image data. This phenomenal continuation of the overlying layer is known as “modal completion.” Panel b is typically perceived as a continuous black shape which is partly obscured by a gray ring. The sense of continuity of a more distant layer hidden behind a near, opaque surface is called “amodal completion.”

formation” that were offered by these authors, which we consider in detail below. Because Kellman and colleagues have claimed that “The identity hypothesis applies to the perceptual process of contour and surface interpolation” (Kellman, 2001, p. 94), we focus attention on the identity hypothesis as it applies to these properties (i.e., surfaces and contours). In what follows,

we also argue that there is no psychologically meaningful concept of “unit” or “unit formation” for which Kellman and Shipley’s claim is, or even *could* be, true. In support of this assertion, we present phenomenological demonstrations, psychophysical data, and theoretical principles that demonstrate that modal and amodal completion exhibit different dependencies on their geometric and photometric context. More specifically, we argue that the identity hypothesis fails for the following reasons:

1. The most common ecological conditions that give rise to modal completion occur when a foreground object is camouflaged by a more distant background. These conditions require a very specific set of luminance relationships to exist between near and far surfaces (namely those that satisfy the conditions of camouflage). In contradistinction, amodal completion can occur whenever one object partially occludes another. This implies that amodal completion should be *independent* of the luminance and contrast relationships at occluding edges, whereas the same is not true for modal completion (since these mechanisms must assess the plausibility of camouflage). In contrast to this reasoning, Kellman and colleagues have explicitly stated that the contour completion process is “color-blind.” We present a series of demonstrations and experiments that provide evidence that the modal interpolation of both surfaces and contours exhibit a dependence on the luminance relationships in a scene, whereas amodal completion processes do not, providing evidence against the identity hypothesis.

2. We theoretically demonstrate that there is a lawful relationship between image contrast and occlusion geometry that introduces a strong constraint on completion processes. This constraint is shown to introduce an asymmetry in how relatively near versus how relatively far contours participate in the completion process. This asymmetry, in turn, is shown to imply that depth must play a critical role in determined *what* is interpolated, not simply *where* interpolated structures are placed in relative depth after interpolation has occurred. Because modal completion involves the completion of a relatively near surface (or contour) relative to a more distant surface (or contour), whereas the converse holds for amodal completion, it will be argued that this asymmetry implies that the completion mechanisms cannot be the same.

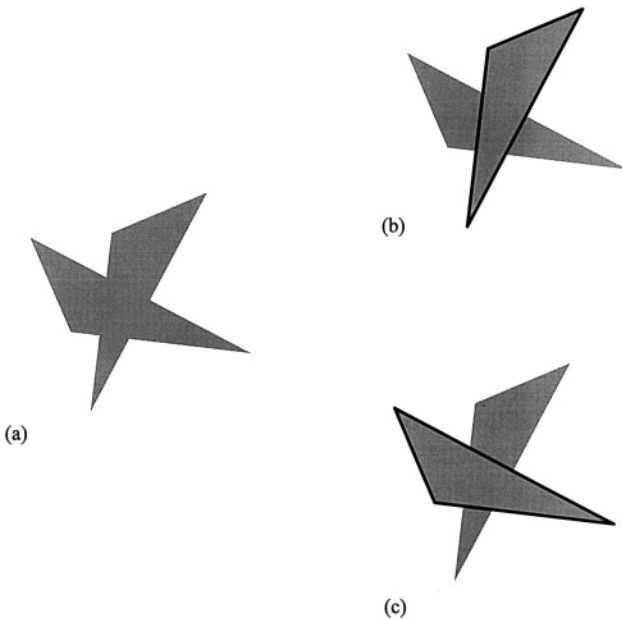
3. We provide perceptual examples in which both the perceived surface structure and the shape of interpolated contours can be altered when the depth relationships in a display are inverted. Shipley and Kellman (1992) explicitly state that the identity hypothesis “would be unavailable if the units in the array or the shapes of interpolated boundaries changed when the modal–amodal switch occurred” (p. 117). Thus, by their own stated criteria, our demonstrations provide the conclusive evidence needed to reject the identity hypothesis.

We begin by reviewing the current evidence that bears on the identity hypothesis and then articulate the theoretical basis for the inherently asym-

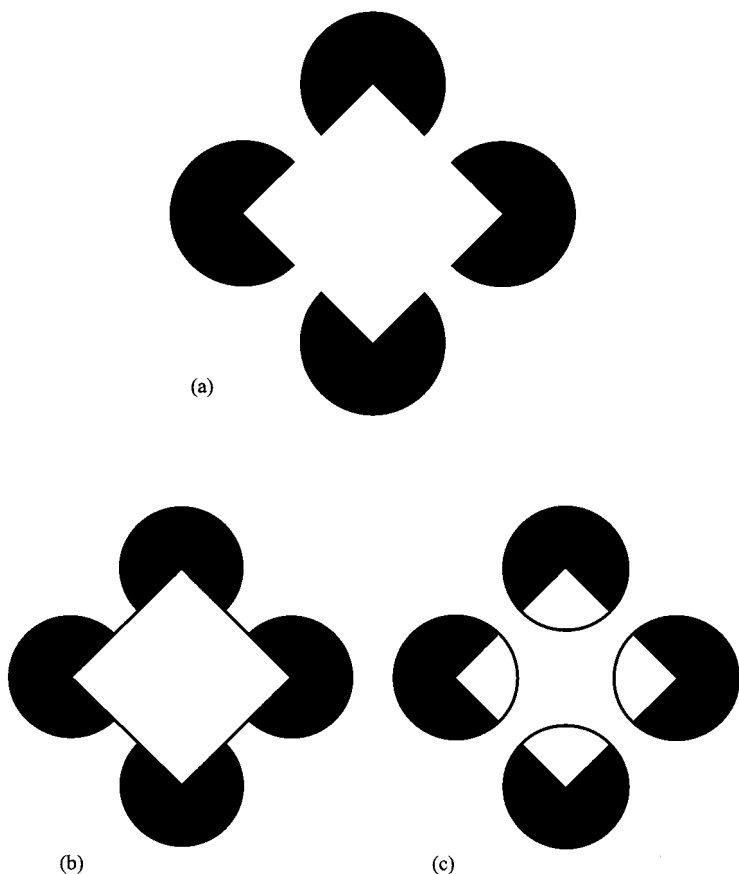
metric relationship between relative depth and interpolated object structure. These arguments will play a critical role in shaping the experiments and demonstrations described below.

### EVIDENCE SUPPORTING THE IDENTITY HYPOTHESIS

Probably the earliest and most cited examples of phenomena that led to the articulation of the identity hypothesis was the observation that the shapes of boundaries and surfaces do not change when certain bistable figures alternate between modally and amodally completed percepts. Two general kinds of bistable displays played a central role in justifying the identity hypothesis: spontaneously splitting objects (or SSOs; see Fig. 2) and Kanizsa figures (see Fig. 3). In SSO displays, a chromatically homogeneous pattern appears to split into two separate objects, one of which appears to occlude the other (Kanizsa, 1979). With prolonged viewing, the depth relationships can appear to flip, causing the objects to alternate between a modal and an amodal ap-

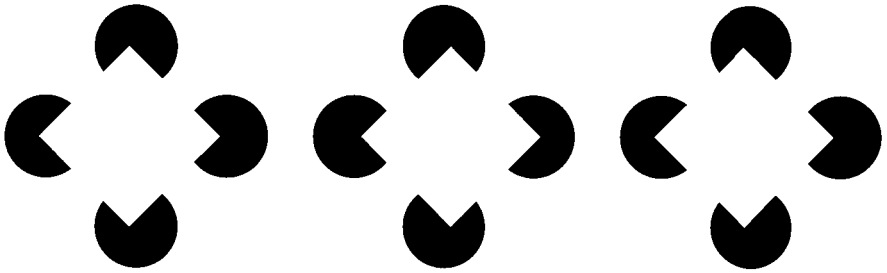


**FIG. 2.** Spontaneously splitting objects. Even though panel a is a single uniform image region, it typically appears to split into two triangular objects, one in front of the other. However, which of the two triangles appears in front reverses with prolonged viewing. The two interpretations are represented in b and c. Kellman and Shipley (1992) note that the units are the same across the two interpretations, claiming that the only change is in the relative depth ordering of the units.

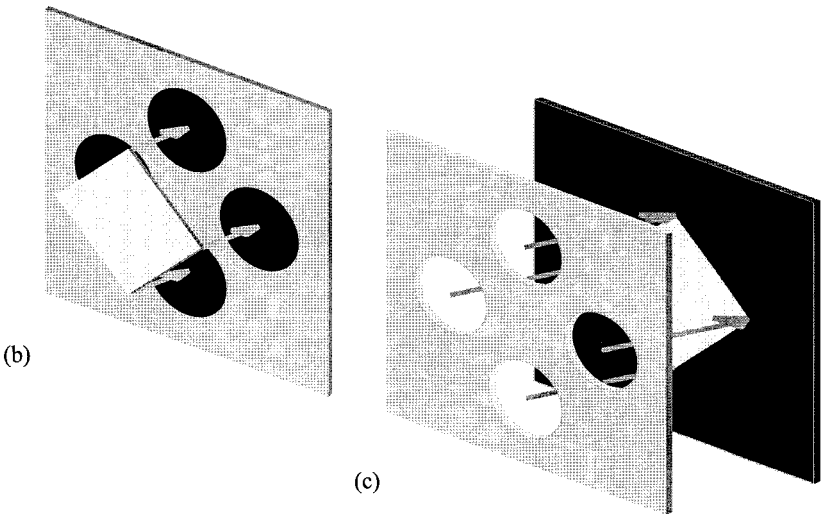


**FIG. 3.** A Kanizsa diamond. The figure in panel a is bistable. It can be seen as a diamond in front of four disks, as in b, or as a diamond through four holes, as in c. Kellman and Shipley (1991) claim that the perceived “units” are identical in b and c.

pearance. A similar result is observed with Kanizsa figures (such as that depicted in Fig. 3). In such displays, the contours of the inducing elements and the illusory figure can appear to alternate between a modal and an amodal appearance, which can be experienced more vividly in their stereoscopic variants (see Fig. 4). The straight inducing elements typically appear to complete and form an illusory figure (here, a diamond) that occludes four amodally completed black disks (Fig. 4b). However, with prolonged viewing (or with stereoscopic information), the depth ordering can flip, and a diamond appears to complete amodally behind four (modally completed) holes (Fig. 4c). As with SSOs, this alternation causes a change in depth order, but the



(a)



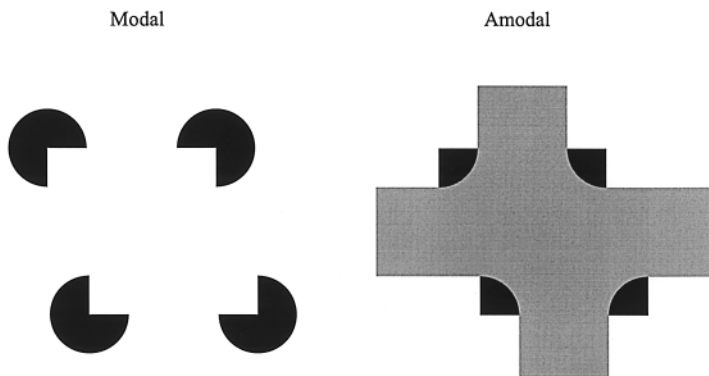
(b)

(c)

**FIG. 4.** (a) A stereogram Kanizsa figure. The two depth orderings are depicted in b and c. In b the white diamond appears to float in front of four disks, which complete amodally behind the illusory diamond. In c the white diamond appears to lie against a continuous black background, visible through four holes. Note that in c the black regions amodally complete to create a continuous black surround for the white figure, but no such completion is observed in b.

shapes of the interpolated boundaries remain unchanged. Kellman and Shipley (1991) claimed that "The units in these various cases do not change; only their depth relations change" (p. 161) and therefore argued that the unit formation process can be dissociated from processes that assign depth to such units.

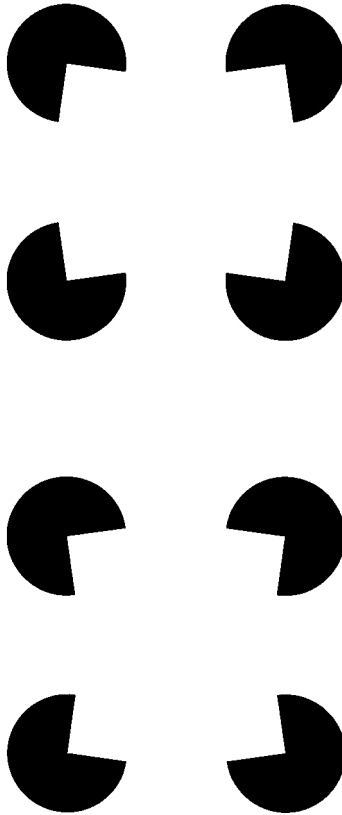
In addition to the phenomenological similarity in the shapes of (some) modally and amodally interpolated boundaries, Shipley and Kellman (1992) performed experiments in which they manipulated the alignment of the con-



**FIG. 5.** Stimuli similar to those used by Shipley and Kellman (1992). The degree of misalignment between the inducers was varied. In the modal case, subjects rated illusory contour strength; in the amodal case they rated perceived unity. Ratings as a function of misalignment were almost identical for the modal and amodal tasks.

tours in a Kanizsa figure and a partially occluded surface (see Fig. 5). They found that contour alignment had a nearly identical effect on observers' ratings of illusory contour strength and the perceived unity of partially occluded surfaces. More recently, a more rigorous behavioral test of the common boundary interpolation mechanism was introduced by Ringach and Shapley (1996). In this paradigm, observers were required to judge whether the inducing elements of a Kanizsa figure were rotated inward or outward for modal and amodal versions of these displays (see Fig. 6). They found that sensitivity to shape changes were virtually identical in these two display types and argued that this provided evidence for a common contour completion process. A similar method was used subsequently by Kellman, Yin, and Shipley (1998), who reported similar results.

In sum, there have been a variety of experimental and phenomenological results that have been used to support the claim that a common interpolation mechanism underlies both modal and amodal completion. According to these authors, the benefit of the identity hypothesis is that it "... disentangles the unit-formation process from the depth ordering of the units formed" (Shipley & Kellman, 1992, p. 117). However, in what follows, we argue that despite the simplifying appeal of this thesis, it cannot account for the facts of perceptual organization for which it was fashioned. It should also be noted that virtually all results that have been treated as support for the identity hypothesis report the absence of differences in tasks involving judgments of modal and amodal displays. This means that the identity hypothesis currently rests on a foundation of negative results, which is clearly a weak foundation on which to base a theory. In what follows, we describe some recent work that casts doubt on the veracity of the identity hypothesis.



**FIG. 6.** Stimuli similar to those used in Ringach and Shapley's (1996) "Fat/Thin task." In the top figure, the Pacman inducers have been rotated so that the vertical contours appear to bow outward ("Fat"). In the bottom figure, they have been rotated so that the contours bow inward, giving the impression of a squeezed square ("Thin"). In various tasks, subjects were asked to state which of the two figures had been presented.

## PRELIMINARY EVIDENCE AGAINST THE IDENTITY HYPOTHESIS

The core postulate underlying the identity hypothesis was stated explicitly by Kellman and Shipley (1991): "Perception of the unity and boundaries of partly occluded objects and perception of illusory figures are the results of an identical unit formation process. As a corollary to this claim, we suggest that the phenomenal differences between these two cases (i.e., between modal and amodal completion), are the results of factors outside of the unit formation process, specifically the depth placement of units formed" (1991, p. 159). The concept of unit formation refers to the problem of understanding how the visual system determines "what goes with what" (Kellman, 2001). So stated, it is clear this concept could be applied to any of a number of

different representational stages, such as the encoding of edges, surfaces, or objects. Recently, Kellman (2001) acknowledged that the identity hypothesis may not hold at object level representations on which top-down recognition processes may operate, but asserted that it held for the bottom-up completion of both contours and surfaces. We therefore focus our assessment of the identity hypothesis at surface and boundary level representations, for which Kellman and colleagues have explicitly stated that the identity hypothesis holds.

One source of evidence casting doubt on the identity hypothesis was described by Ringach and Shapley (1997). Although these authors found identical shape discrimination performance for modal and amodal displays for some display durations, they also reported a substantial difference in modal and amodal discrimination when the displays durations were sufficiently short. Ringach and Shapley (1996) recognized that this asymmetry implies that there is “. . . some fundamental difference between modally and amodally completed contours” (p. 3049). However, they suggested that this could be due to the difference in the local features used to create the two displays (such as contour junctions) rather than a difference in modal and amodal interpolation mechanisms *per se*.

More direct evidence for an asymmetry in the modal versus amodal contour completion has been observed in a stereoscopic “cross” display (introduced by Nakayama & Shimojo, 1992; see Fig. 7). In this figure, only the vertical contours carry unique disparity (depth) signals, which means that the (ambiguous) depth of the horizontal contours must be derived from the disparities of the vertical contours. There are a number of possible interpretations of this figure. One interpretation involves decomposing the cross into two bars, such that the nearer bar appears to occlude the more distant bar (Figs. 7b and 7d). The other interpretations involve some form of smooth interpolation of depth, such as a uniform slant between the depths of the vertical contours (Figs. 7c and 7e). Anderson and Julesz (1995) used this stimulus to assess the identity hypothesis by comparing the two possible depth interpretations of the horizontal and vertical bars. If a common completion mechanism underlies both modal and amodal completion, then there is no reason to expect any differences in the stability or clarity of the two depth configurations. This is because a switch in relative depth just determines which contours (vertical or horizontal) are modally or amodally completed. If both forms of completion are driven by a common mechanism, then there is no reason to expect a difference in these patterns. Indeed, this pattern is simply a SSO, so the identity hypothesis asserts that the surface and contour completion mechanisms should be identical in these two depth configurations. However, in contrast to the prediction of the identity hypothesis, Anderson and Julesz (1995) reported that observers tended to perceive the occlusion percept when the horizontal bar appeared behind the vertical bar, but observed the occlusion percept less frequently for the reverse depth ordering

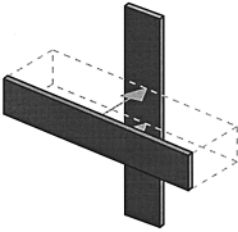
(a) Stereogram



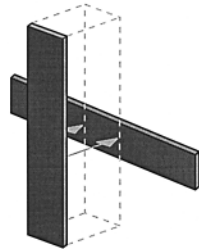
Horizontal Near

Horizontal Far

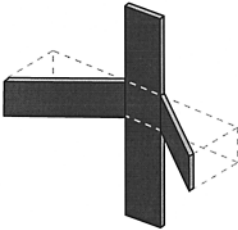
(b)



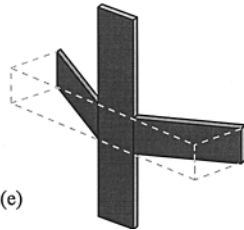
(d)



(c)



(e)



**FIG. 7.** An untextured cross stereogram, introduced by Nakayama and Shimojo (1992). Anderson and Julesz (1995) used this stimulus to assess the identity hypothesis. Only the vertical contours carry disparity information, so the perceived depth must be interpolated by the visual system at all other locations. When the horizontal bar has near disparity the figure is seen as either b or c. When the horizontal bar has far disparity, it tends to be seen as d; interpretation e is rarely reported.

(i.e., the depth of the horizontal bar was much less stable, alternating between that depicted in Figs. 7c and 7b). A discrimination experiment also revealed that observers were more sensitive to depth differences between the two bars when the horizontal bar appeared behind the vertical bar compared to the reverse depth order. This result is difficult to reconcile with a model that places contour and surface completion processes prior to the localization of these objects in depth (such as Kellman & Shipley's), since the contour completion process should have already caused the object to split into two separate objects, and there is nothing in this theory to predict an asymmetry in sensitivity and stability. Anderson and Julesz (1995) argued that these asymmetries arose from the relative frequency that camouflage versus partial occlusion is encountered in natural scenes. While partial occlusion occurs in virtually all natural scenes, camouflage occurs only when a nearer surface is identical to its background. If these computations are performed by distinct mechanisms, then we would expect that the perception of camouflage would be less stable than the perception of partial occlusion, at least if these (different) mechanisms were tuned to the relative frequencies of these different sources of image fragmentation.

More recently, there have been a number of studies in the attention literature that also provide suggestive evidence for differences in the mechanisms underlying modal and amodal completion. Davis and Driver (1994, 1998) performed search experiments and found that search for modally completed Kanizsa figures was much more efficient than their amodal counterparts. A similar finding was subsequently reported by Gegenfurtner, Brown, and Rieger (1997) using a different paradigm. Davis and Driver (1997) also reported that object based attentional cueing was observed for modally completed surfaces, but no such facilitation was observed for amodally completed figures. Taken together, these studies suggest that modal and amodal completion are either subserved by distinct mechanisms, or that attention operates differently on these two forms of completion.

In addition to this psychophysical evidence, physiological studies have also provided evidence that distinct mechanisms underlie modal and amodal completion. Indeed, the identity hypothesis is by its very nature a claim about mechanism, so the veracity of this claim must ultimately be assessed physiologically. There are at least two physiological studies that run counter to the identity hypothesis. Peterhans and von der Heydt (1989) reported that cells in V2 responded vigorously to displays that generated a percept of a *modally* completed bar (subjective contour displays), but did not respond to displays that generated a percept of an *amodally* completed bar. These displays were very similar to those employed in Kellman et al.'s and Ringach and Shapley's psychophysical studies, so they bear directly on their common mechanism thesis. More recently, Sugita (1999) found that both simple and complex cells in V1 fired vigorously to an *amodally* completed bar behind a square occluder, but did not respond when the square occluder was given a disparity

that should invoke a modally completed contour. Thus, cells that responded to modally completed contours did not respond to amodal versions of the same display, and cells that responded to amodally completed contours did not respond to modally completed displays. These studies reveal that modal and amodal contours are dissociated at the earliest stages of cortical processing where orientation information becomes explicit, providing a serious challenge to the identity hypothesis at either surface or contour level representations.

In sum, the existing literature is mixed about the current status of the identity hypothesis. However, with one exception (Anderson & Julesz, 1995), the majority of studies that cast doubt on the identity hypothesis were not explicitly designed to assess its veracity. In what follows, we will provide theoretical arguments, demonstrations, and data to directly assess the identity hypothesis as it applies to the interpolation of both surfaces and contours. In anticipation, our results provide evidence against the identity hypothesis and suggest that distinct mechanisms underlie the interpolation of modal and amodally completed surfaces.

### ASSESSING THE SURFACE-LEVEL IDENTITY HYPOTHESIS

As noted above, it has been claimed that the identity hypothesis holds at both the level of contour and surface representations (see, e.g., Kellman, 2001). In this section, we argue that it can be shown that the (surface level) identity hypothesis can be rejected by simply considering in greater detail one of the key figures that originally *inspired* the identity hypothesis—namely a Kanizsa figure (such as that depicted in Fig. 3). In this display, the interpolated boundaries within the Kanizsa figure have the same shapes when they are modally or amodally completed, forming one diamond and four circular figures. This is presumably what motivated Kellman and Shipley's claim that a single "unit formation" process underlies both modal and amodal completion. However, this is where the identity between these two percepts ends. When the Kanizsa figure appears as an illusory diamond occluding four black disks, a surface-level representation decomposes the image into a diamond, four black disks and a white background surface (Fig. 4b). When the diamond appears to complete *amodally*, however, a surface-level representation of this percept contains a white occluding surface containing four holes, an amodally completed diamond, and a uniform black background on which the diamond lies (Fig. 4c). Thus, at a surface-level representation, the units clearly *do* change during the transitions between a modal and an amodal appearance in such Kanizsa displays. In the modal displays, there are four black "units" (disks), and no completion is observed between them. In the amodal display, there is only one black "unit." *Note that this black surface (or perception of empty space) must arise from the amodal interpolation process, since it is not present in the image data.* The implications of this fact should be clear: The unit formation process cannot

be dissociated from the placement of units formed in depth, and hence, this simplification is, to quote Shipley and Kellman (1992), “unavailable.”

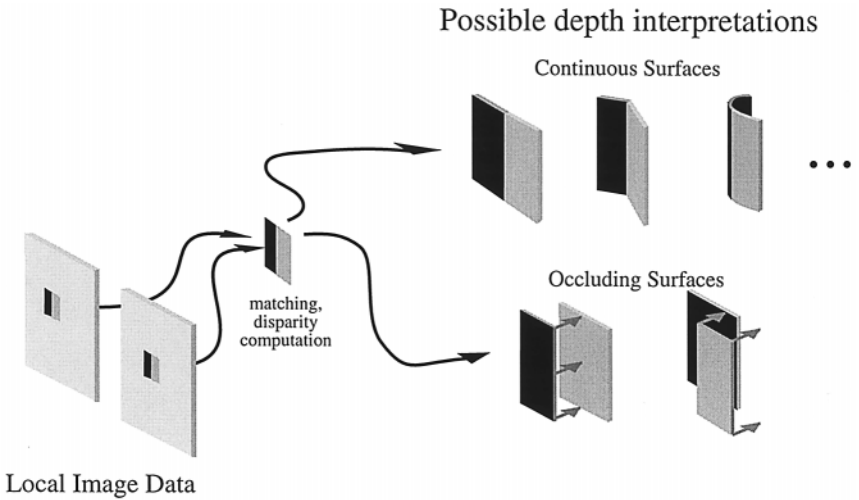
One possible defense of Kellman and Shipley’s claim that the “units” remain unchanged when the Kanizsa figure alternates between a modal and an amodal appearance is to offer a definition of “unit” for which this claim would be true. It would appear that only one such definition is possible, namely one in which the term “unit” refers to a closed contour and the image region it encloses.<sup>1</sup> However, it is a relatively simple matter to demonstrate that this conclusion would contradict any psychologically meaningful notion of “unit.” Consider Rubin’s vase–face display. In Rubin’s figure, the shape of the contours and the image regions they enclose remain unchanged when the percept alternates between a single vase and two faces. If the term “unit” simply referred to a closed contour and the region it encloses, then this definition would imply that there is no change in the perceived “units” in Rubin’s demonstration despite the fact that both the *shapes* of the objects and the *number* of objects change when the percept alternates between a vase and two faces. Clearly, such a definition fails to capture any psychologically meaningful sense of “unit.” Thus, we must conclude that this concept of “unit” fails to capture the psychological meaning of this term. In the following section, we argue that the primary shortcoming of the identity hypothesis is that it fails to appreciate the consequences that occlusion has on the generation of near and far contour segments (or local image contrast more generally) and the constraints this asymmetry places on modal and amodal completion.

### THE RELATIONSHIP BETWEEN LOCAL IMAGE CONTRAST AND RELATIVE DEPTH

The main intuition behind the identity hypothesis is that “. . . the process of locating units in depth is separable from the process of unit formation” (Kellman & Shipley, 1991, p. 162). In this section, we describe a new theoretical insight (Anderson, submitted) that demonstrates that the process that places completed units in depth is *not* independent of the process that completes the units. We argue that relative depth is not simply a space into which completed units are placed. Rather, we argue that *relative depth determines what the elements are that participate in the completion process*, which in turn constrains what is actually completed.

The main reason for the dramatic shift in surface structure experienced with figures such as the Kanizsa pattern lies in what one of us has termed the *contrast depth asymmetry principle* (Anderson, submitted). The main intuition needed to grasp this principle is the realization that occlusion introduces an asymmetry in the visibility of relatively near and far surfaces.

<sup>1</sup> This definition was offered by an anonymous reviewer as a way of defending the identity hypothesis.



**FIG. 8.** A contour which carries a depth signal (e.g., disparity) is inherently ambiguous. Two main classes of world states could have given rise to the contour: The contour could have originated from a single continuous surface (e.g., a reflectance edge or cast shadow), or it could have originated from an occlusion event. In the occlusion case, the border ownership of the contour is ambiguous. Nonetheless, in all configurations, both sides of the contour are constrained to be at least as far as the depth signal carried by the contour. This introduces a fundamental asymmetry in the role of near and far contours in determining surface structure (see text for details).

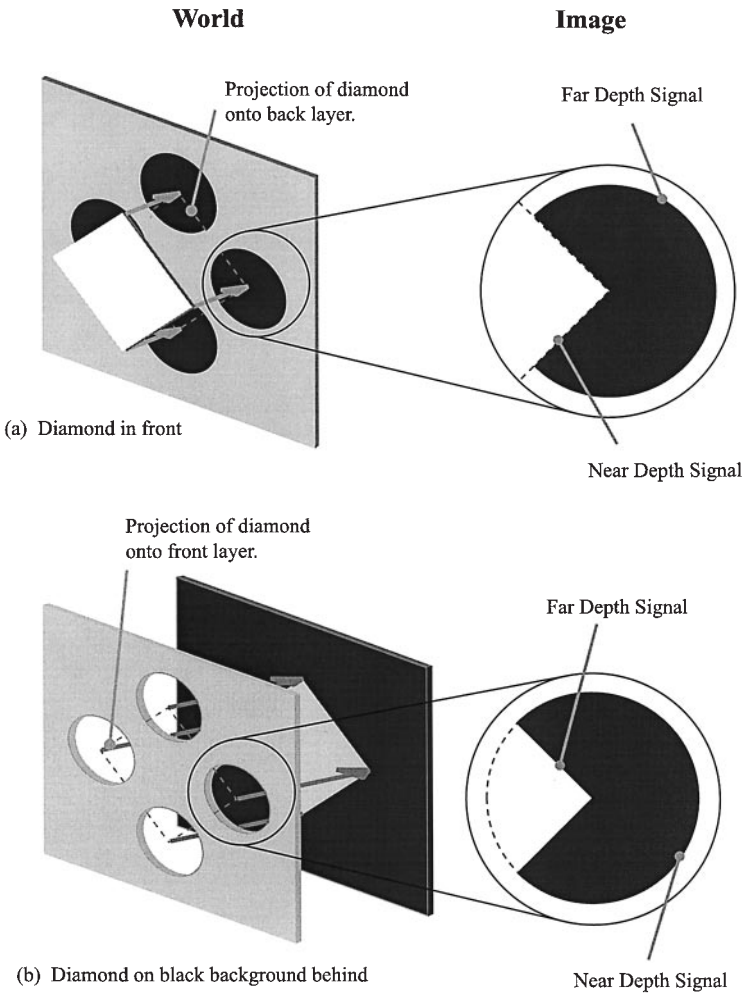
Nearer surfaces interrupt the projection of more distant surfaces, whereas more distant surfaces do not interfere with the projection of nearer surfaces. As we show below, this simple but fundamental geometric fact limits the possible depth relationships that can be attributed to a local image contrast, which in turn constrains interpolation processes.

To understand this principle, consider a simple luminance discontinuity (hereafter “contour”) that has been assigned a local depth value (see Fig. 8). Although the arguments that follow apply to any source of depth information, for exposition purposes, we assume that the source of information about relative depth is binocular disparity. We also assume that the two sides of the contour are untextured, so that the only depth information present in the vicinity of the contour arises from the contour itself (via its disparity). The problem confronting the visual system is to determine the surface events consistent with this local image data. In general, we can distinguish two broad kinds of surface events that are consistent with a contour that has a depth signal (such as disparity) associated with it. One possibility is that the contour arose from events that occur along a continuous surface, such as a change in reflectance (color or lightness), surface orientation (such as a fold), or an illumination change (due to shading or shadows). In all such cases,

the two sides of the contour are “connected” in the sense that they lie at adjacent positions in depth. The other kind of surface events that could have given rise to a contour is an occlusion relationship. When this occurs, there are two possible depth orderings consistent with the same local image data: one side of the contour is the occluding surface, and the other side is the occluded surface (or background). This means that one side of the contour—the occluded surface—is more distant in depth than is given by the disparity of the contour. Said differently, because the occluding surface “owns” the edge (Koffka, 1935; Nakayama, Shimojo, & Silverman, 1989), it is located at the depth specified by the local disparity signal (or other depth signal). However, the depth of the occluded surface can appear at any depth *behind* the occluding contour. Note that in an occlusion configuration, there is only one depth (disparity) signal, but two depths that must be recovered.

This geometric relationship between contours (local image contrast), disparity (depth), and surface structure can be captured by the following principle (the contrast depth asymmetry principle): “The two sides of a luminance discontinuity with an associated depth value are constrained to either appear at the depth of the contour, or one side of the contour can appear *more distant* in depth.”

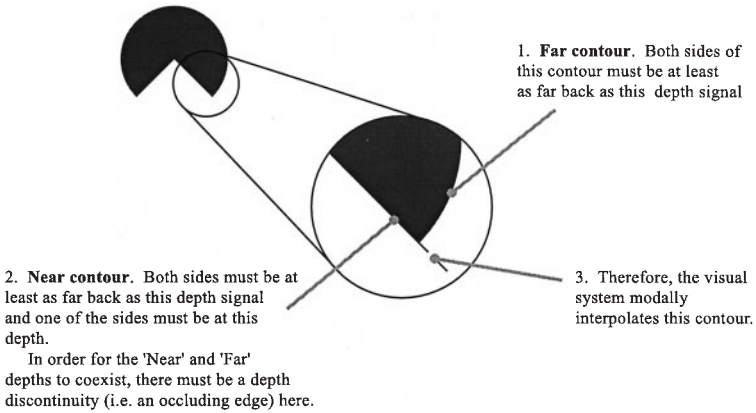
It should be noted that this constraint only applies *at* the location of the contour (i.e., the adjacent surfaces could be tilted or curved toward the observer on either side of the luminance discontinuity). Although this principle appears simple in form, it has profound consequences on how the image regions forming contours (or local contrast signals more generally) can be interpreted and/or interpolated. In particular, this constraint requires that both sides of any contour must appear *at least as far* as the depth of this local contrast signal. This principle holds locally for all contours (or local image contrast more generally). Perhaps the best way to demonstrate the potency of this principle is to show how it explains the transformation in perceived surface structure experienced in the modal and amodal variants of Kanizsa figures. Consider the geometry of the contour junctions in the Kanizsa displays depicted in Fig. 4. The near and far contours of the inducing elements (“pacmen”) intersect to form L-junctions in different depth planes (see Figs. 9 and 10). When the contrast depth asymmetry principle is applied to each contour, it predicts the asymmetry in perceived surface structure that occurs in these patterns. First, consider the case where the interpolated diamond appears in front. In this configuration, the curved arcs are more distant than the straight contour segments of the diamond. The contrast depth asymmetry principle requires that the luminances adjacent to the curved arcs appear *at least* as distant as these arcs in depth. This causes the regions adjacent to both sides of the curved contours to recede to (at least) this distance in depth. This, in turn, transforms the local L-junctions formed by the intersection of the curved arcs and the straight contours into T-junctions (see Fig. 10a), disambiguating the border ownership of the near contour: The



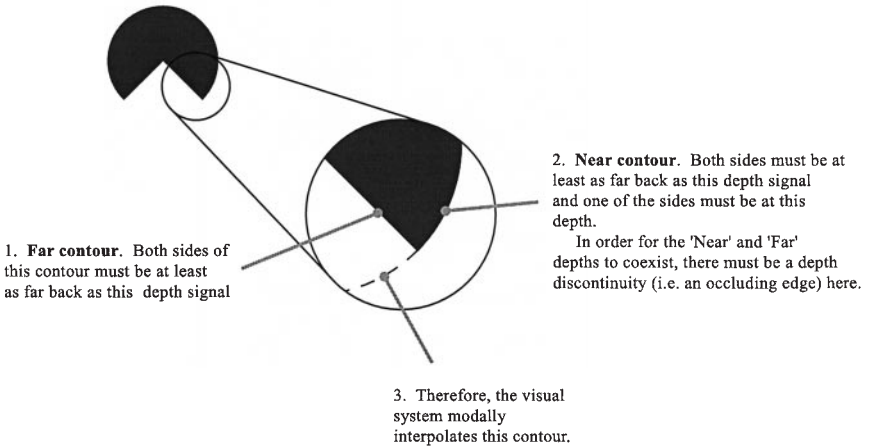
**FIG. 9.** (a and b) The inducers of a Kanizsa figure contain L-junctions. In the stereo version of the figure, the two contours that make up these junctions carry different disparity signals. This figure demonstrates how these L-junctions are formed. Note that two depths are involved. The disparities carried by the contours that form the L-junction constrain the depth estimates of the various surfaces, and this in turn constrains the modal interpolation (see Fig. 10).

occluding surface corresponds to the region along the top of the T-junction. However, when the depth of these contour segments is reversed, the straight contour segments become the more distant contours. In this depth configuration, the contrast depth asymmetry principle requires that both sides of these straight contour segments must now appear at least as distant as these contour segments. This causes both the white and the black regions adjacent to the

**(a) Diamond in Front**



**(b) Diamond on black background behind**



**FIG. 10.** As shown in Fig. 9, the contours that form the L-junctions of Kanizsa inducers carry different depth signals. The contrast depth asymmetry principle constrains the depths of the surfaces on either side of these contours. The only way that these constraints can be satisfied simultaneously for the "near" and "far" contours is if the world contains a depth discontinuity (i.e., an occluding edge). This depth discontinuity must belong to a near surface, so the visual system interpolates an illusory surface. In a the disk owns the far boundary. In b, by contrast, this boundary is owned by the near surface (it is the edge of the portholes). This means the far surface is unbounded and therefore amodally completes to form a continuous black background surrounding the amodally completed diamond (see Fig. 9).

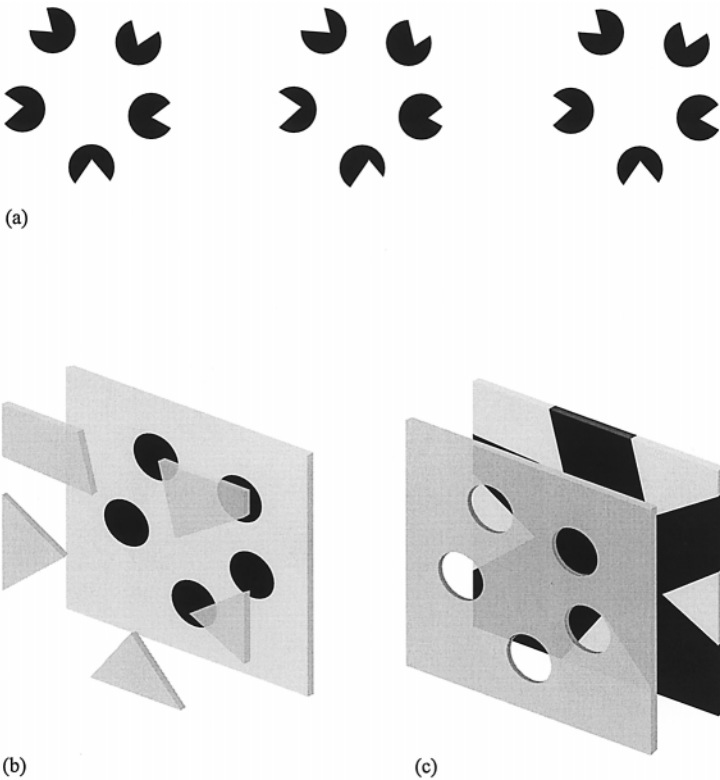
straight contours to recede in depth, generating a new T-junction that uniquely specifies that the outside of the curved arcs are an occluding surface (Fig. 10b). Importantly, the recession of the black regions in depth initiates the amodal interpolation of the black surface structure behind the circular occluding holes, which did not occur in the reverse depth ordering.

In sum, the contrast depth asymmetry embodies an inescapable geometric and perceptual constraint that articulates why the unit formation process *cannot* be dissociated from the relative depth of the contour segments. The contrast depth asymmetry principle is a local constraint that expresses how local image contrast can arise from the projective geometry of occluding or continuous surfaces, which gives rise to asymmetries in the role of near and far image contrast in completion processes. In what follows, we present new demonstrations illustrating the dramatic changes in surface structure that can occur in modal and amodal completion that arise from the constraints imposed by this principle as well as a new demonstration illustrating differences in the shapes of modally and amodally completed contours.

#### NEW TRANSFORMATIONS IN SURFACE STRUCTURE GENERATED BY MODAL AND AMODAL COMPLETION

In the previous section, we showed that there is an inherent asymmetry in the depth information contained in relatively near and far image contrasts and argued that this causes an inherent asymmetry in the elements that participate in modal and amodal completion. In this section, we present new demonstrations illustrating the asymmetric relationship between modal and amodal completion of both surfaces and contours.

The contrast depth asymmetry principle states that the luminance values generating a contour must be equal to, or more distant than, the depth of the contour. When applied to contour intersections, this implies that the image regions adjacent to the more distant contour must recede to at least the depth of this contour. However, it is important to note that this is *all* that can be derived about surface structure of the more distant contour on the basis of this local information; there is no local information that can be used to disambiguate the figure-ground relationship of this contour. In the “porthole” configuration of the Kanizsa figure, the interpolated contours generate a closed diamond-shaped figure. The appearance of this region as figure is presumably caused by the tendency for closed regions to appear as figures (rather than holes), not by any local depth information generated by the stereoscopic information present in these regions. This ambiguity suggests that it may be possible to induce an even more dramatic change in surface structure in the modal-amodal variants of such displays by eliminating this closure cue to figure-ground relationships. Note that in these figures, the similarity in the “units” formed in the modal and amodal cases may be due to the presence of closed contours in both depth configurations. To assess this



**FIG. 11.** (a) A new stereo demonstration of how relative depth alters perceived surface structure. The two depth orderings were created by simply interchanging the two eyes' views. (b and c) Three-dimensional renderings of the two interpretations of the new-variant Kanizsa figure shown in a. The transparency of the near layer is included only so that both the near and far surfaces can be depicted simultaneously. In b, five disks appear to be occluded by five distinct surface fragments. In c, by contrast, a single irregular black "star" appears to lie on a continuous white background, which is visible through five holes in a continuous overlying layer. In this depth ordering the black shape tends to appear as figure.

possibility, we constructed the stereogram depicted in Fig. 11. The contours of the inducing figures have been rotated outward in a manner to prevent contour completion from occurring in either the modal or amodal variants of the displays. When the straight contours of the inducing elements appear in front of the curved contour segments, the white wedges appear as unconnected surface patches that occlude five black disks lying on a white background. Note that in this configuration, the perceptual "units" (i.e., surfaces) include five white occluding surface patches, five disks, and a white background (see Fig. 11b). However, when the depth relationships are reversed, a very different percept is observed. Observers now report the appearance

of a single, irregularly shaped *black* surface lying on a white background behind five holes (see Fig. 11c). In this configuration, there are only three units (or surfaces): the single black surface, its white background, and an occluding surface containing five holes.

The point of this demonstration is to show that the transformation from a modal to an amodal display can cause large changes in perceived surface structure that do not depend on the interpolation of contours. In the original Kanizsa figure, we observed a shift in the surface structure of the background of the Kanizsa diamond, but the figure-ground relationships of the diamond/background borders remained the same for both the modal and amodal cases. However, in the demonstration depicted in Fig. 11, the interpolation of the black surfaces behind the occluding holes can generate a shift in the border ownership assigned to the contour as well as a transformation in the number of units perceived. Indeed, this demonstration reveals the insufficiency of using contours as the primary building block for a theory of object interpolation and unit formation. A theory that asserts the identity of "units" based solely on the shapes of interpolated contours ignores the transformation in structure that can accompany shifts in border assignment. Rubin's classic face-vase demonstration as well as the host of Gestalt figure-ground displays all attest to the role of surface level representations in shaping the interpretation of contours and the dramatic transformations in the perceived shapes of surfaces and objects that can accompany such shifts. Although Kellman and Shipley (1991) discuss these phenomena, they apparently did not appreciate the theoretical significance that they have on a theory of unit formation. Kellman and Shipley have suggested that surface interpolation "complements" boundary interpolation, but the primary role of surface interpolation in their theory was to simply spread surface quality between interpolated boundaries (Kellman & Shipley, 1991; Yin et al., 1997). The demonstration depicted in Fig. 11 shows that surface interpolation is not restricted to occur between interpolated boundaries, since there is no clear percept of the boundaries in these figures.

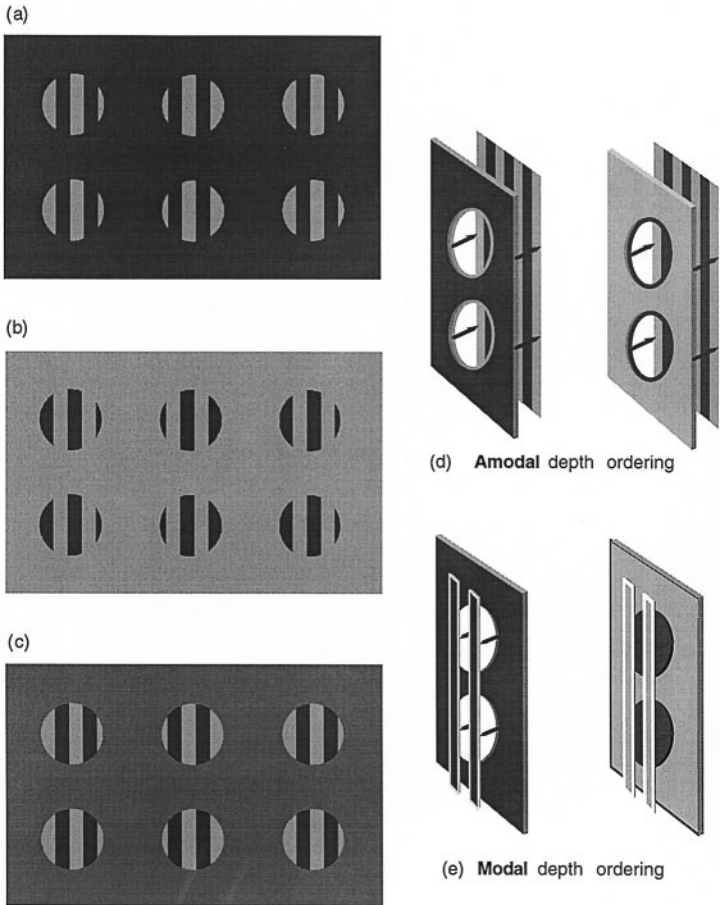
#### MODAL AND AMODAL COMPLETION EXHIBIT DIFFERENT LUMINANCE DEPENDENCIES

The demonstrations described above reveal that there is a fundamental asymmetry in the information contained in relatively near and far contours. This asymmetry can transform the elements that participate in the completion process and can cause transformations in the number and shapes of modally and amodally completed surfaces. However, to this point, there is no evidence to suggest that any difference exists between modal and amodal *boundary* completion. In the examples considered thus far, the modally and amodally interpolated boundaries have been identical and have yielded equal performance data when used in a shape discrimination task. However, as

noted above, there are differences in the ecological conditions that will support modal and amodal completion: Amodal completion arises when objects or surfaces are partially obscured by an occluding surface, whereas modal completion will only be initiated when a nearer surface is camouflaged by a more distant surface. This difference suggests the possibility that asymmetries in modal and amodal boundary completion might be observed if the luminance conditions were not consistent with camouflage. The majority of experiments that have been performed to date have not explored the luminance dependence of these two forms of completion, so it is possible that the apparent similarity in these two forms of completion may only occur for the luminance regimes that have been studied to date.

To appreciate the relevance of luminance in constraining modal completion, consider the square-wave gratings depicted in Fig. 12. These stimuli were made by embedding a square-wave grating in circular apertures. The disparity of the curved aperture boundaries and the straight contours of the grating can be manipulated independently, as can the luminance relationships between the square wave pattern and the adjacent surround. When the grating is placed behind the aperture boundaries, it appears to complete amodally and form a single, opaque surface behind the two circular apertures. This percept occurs for all luminance values of the adjacent surround (see Fig. 12d). However, when the depth relationships are reversed, a very different set of percepts emerge that depend critically on the luminance of the adjacent surround. When the surround is light gray, the gratings appear to split into two surface layers. The far layer appears as dark gray disks, and a pair of light gray stripes appear to complete modally across the disks' boundaries (Fig. 12e). When the adjacent surround is changed to dark gray, the gratings again appear to split into two surfaces separated in depth. However, now the gratings appear as two distant *dark gray* disks that are partially occluded by a series of *light gray* stripes that modally complete across the boundaries of the dark gray disks. In this luminance condition, the interpolated (dark) stripes are coincident with the luminance minima of the grating pattern. Importantly, when the luminance of the surround is a gray that falls between the extrema of the grating, the percept of these displays is unstable and no modal completion is observed (see Fig. 12c).

The critical aspect of these demonstrations for the purposes of the present article is that they demonstrate large differences in *what* is completed in the modal and amodal variants of these displays. When the grating appears to complete amodally behind the aperture boundaries, both the contours and the dark and light components of the grating participate in the completion process. Both the surface structure and the contours are completed in this depth configuration and are independent of the luminance of the surround. However, when the depth relationships are reversed, a very different set of percepts is observed. When the background is an intermediate luminance, neither the contours nor the surface structure are seen to complete across the



**FIG. 12.** The stereoscopic stimuli used in Experiments 1 and 2. These displays demonstrate clear asymmetries between modal and amodal completion. In particular, *amodal* completion between the top and bottom sets of gratings is essentially independent of the surround luminance (in each case consisting of a single striped surface viewed through two circular windows, as depicted in schematic d), whereas *modal* completion depends critically on the luminance of the surround. This dependence manifests itself in two ways. First, a coherent modal percept is obtained only when the surround is “dark” or “light,” but not when it is “intermediate.” Second, the modal percepts differ strikingly for light and dark surrounds. In the former case, light-colored stripes are seen completing over two dark disks, whereas in the latter case, dark-colored stripes are seen completing over two light disks (this is shown in the schematic e).

gap, in contrast to the claim of Kellman and colleagues that the contour completion process is “color-blind.” When the background is equal to either the maxima or minima of the grating, a very different set of percepts result. In such conditions, the grating appears to split into two surfaces, and only the maxima or minima of the grating appears to complete modally, and the other component of the grating completes amodally to form two disks. In order to experimentally document these observations, we performed rating experiments that were nearly identical in structure to those that have been performed previously to support the identity hypothesis. In addition, we also had observers perform a contour alignment (vernier) task. One of the primary sources of evidence that has been used to uphold the identity hypothesis is the identical discrimination performances in displays generating percepts of modally and amodally completed contours. If the contour completion process is color-blind (as the identity hypothesis asserts), then we would expect the discrimination accuracy of the modal and amodal targets to be identical and independent of the luminance of the surround. These experiments are described below.

## EXPERIMENT 1

The goal of Experiment 1 was to document the phenomenology of perceptual completion associated with the displays considered above (Fig. 12). We manipulated the disparity of the gratings relative to the circular aperture boundaries, the luminance of the background, and the vertical separation between the pair of gratings within each display. Subjects rated the perceived strength of the completion for both modal and amodal variants of the display as a function of the vertical separation between them for three different surround luminances. Based on the arguments presented above, we hypothesized that the ratings for near disparity (i.e., modal case) would depend critically on the luminance of the background, whereas those for far disparity (i.e., amodal case) would be independent of background luminance.

### *Methods*

*Observers.* Nineteen subjects participated in the experiment. They were recruited from within the MIT community and were paid for their participation. All were naive to the purpose of the experiment and had normal or corrected-to-normal vision.

*Stimuli and apparatus.* Each stimulus display consisted of two identical sets of square-wave gratings enclosed within circular boundaries—one presented below the other (see Fig. 12). The displays were viewed stereoscopically so that the gratings could be given either near or far disparity relative to the circular boundaries. The diameter of the circular boundaries was  $3^\circ$  of visual angle. The spatial frequency of both sets of gratings was 0.735 cycles/degree (period =  $1.36^\circ$ ), the peak luminance was  $27.1 \text{ cd/m}^2$ , and the trough luminance was  $5.15 \text{ cd/m}^2$ . The gratings within the two circular regions always had identical phase and disparity. The luminance of the background and the separation between the two circular regions were varied.

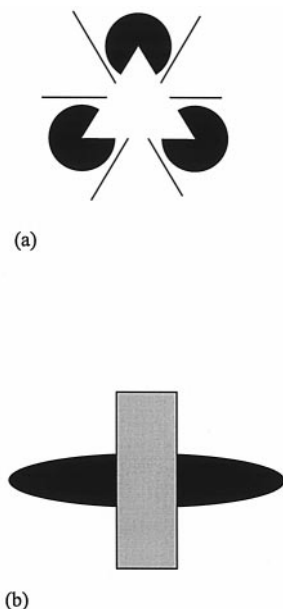
All displays were presented on a high-resolution ( $1600 \times 1200$ ) Mitsubishi Diamond Pro 91TXM monitor driven by a Power Macintosh G3 (using VisionShell Software), and viewed through a mirror stereoscope at a distance of  $\sim 99$  cm.

*Design.* Three independent variables were manipulated: the sign of the disparity given to the gratings relative to the circular boundaries ( $+22.86$  and  $-22.86$  arc min), the vertical separation between the two gratings ( $0.82^\circ$ ,  $2.18^\circ$ ,  $3.53^\circ$ , and  $4.89^\circ$ ), and the luminance of the background ('light,' 'mid-grey,' and 'dark'). The light and dark backgrounds corresponded to the peak luminance ( $27.1$  cd/m<sup>2</sup>) and trough luminance ( $5.15$  cd/m<sup>2</sup>) of the gratings, respectively, whereas the midgray corresponded to an intermediate value ( $13.72$  cd/m<sup>2</sup>). The dependent measure was the rating value (on a scale from 0 to 10) given by the participants to indicate how strongly the gratings appeared to complete across the gap.

*Procedure.* The procedure consisted of three phases: (a) a stereoscopic test phase to determine whether observers were capable of perceiving stereoscopic depth, (b) an introduction phase to acquaint participants with the phenomena of modal and amodal completion, and (c) the experimental phase.

Participants were first shown test stereoscopic displays to ensure that they had no difficulty perceiving depth from stereoscopic images. Two classes of displays were used: (1) a random-dot stereogram, whose disparity was consistent either with a small square floating in front of the background or a small square-shaped hole through which an underlying surface could be seen; and (2) a sinusoidal grating within a single circular boundary surrounded by a dark background. As noted above, depending on the sign of the relative disparity, this gives rise either to the percept of a single surface seen through a circular aperture or of dark stripes floating over a light disk.

Following the stereo test, participants were acquainted with the phenomena of modal and amodal completion using the displays in Fig. 13. They were first shown the display on top



**FIG. 13.** (a and b) The displays used to acquaint naive observers with the phenomena of modal and amodal completion.

of Fig. 13 and were informed that it is typically seen as a white triangle overlying three black disks and is thus an example of visual completion in which vivid contours are seen where none exist on the page. All participants confirmed experiencing this percept. Participants were then shown the display at the bottom and informed that this pattern is typically perceived as a single black oval partly hidden behind a rectangular bar, even though its contours are not actually visible behind the rectangular bar. All participants stated that this was an accurate description of their percept.

The experiment was then run in two separate blocks: one for the near disparity (modal) condition and the other for the far disparity (amodal) condition. The ordering of these two blocks was randomized across subjects. Subjects were instructed that on each trial they would see two circular disks with stripes inside them, separated by a gap, and that they were to rate the strength of completion of these stripes across the gap.

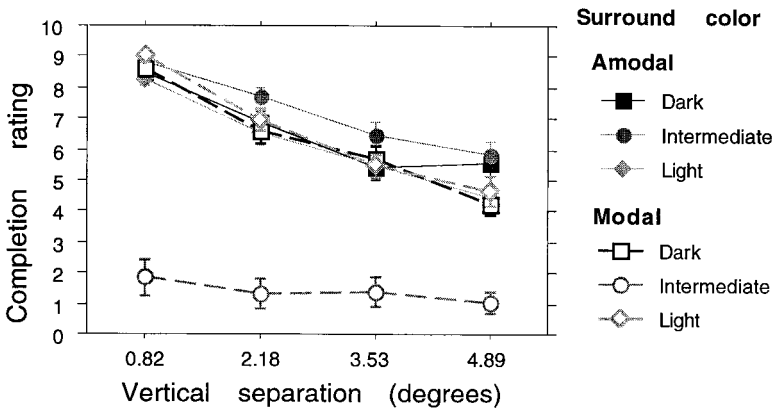
Prior to the modal block, participants were instructed that on each trial their task would be to (1) indicate the color of the stripes that they saw completing across the gap and (2) rate the clarity with which they saw the stripes complete across the gap on a scale from 0 to 10. The color task involved a choice from four options: "dark," "midgray," "light," and "none." The meanings of the three achromatic colors were explained relative to the square-wave grating, and it was indicated that the choice "none" was to be used when they did not see any stripes complete across the gap. Participants were shown a modal display with dark surround and the shortest level of separation ( $0.82^\circ$ ) as an example of "fairly strong completion." However, it was stressed that they should not yet assign a rating value to it because they would be shown all of the stimuli in random order before the experimental session. The goal of this session was to give subjects a sense of the range of completion strengths that they would see in the experimental session and to allow them to calibrate their own rating scales.

Prior to the amodal block, participants were instructed that on each trial their task would be to rate the perceived unity of the two sets of stripes on a scale from 0 to 10. There was no color task in this case because there is no perceived spreading of color in the amodal case. It was stressed that ratings were to be based on how strongly the two sets of stripes appeared to form a single surface that continued behind the occluding region separating the two circular windows. Participants were shown an amodal display with a dark surround and the shortest level of separation as an example of "fairly strong completion." As in the modal case, they were asked to not yet assign a rating value to it because they would be shown all of the stimuli before the experimental session in order to allow them to calibrate their rating scale.

The instructions were followed by a session during which all stimuli that were presented in the subsequent experimental block were shown in random order. Each stimulus display was presented on the screen for 2 s, preceded by a fixation cross for 1 s. Participants did not have to respond during this session; they simply viewed the displays and were asked to consider the ratings that they might give to rate their strength of completion. The goal of this session was to acquaint the observers with all of the experimental stimuli and to give them a sense of the range of completion strengths they would see.

In the experimental session, each trial began with a fixation cross for 1 s, followed by the stimulus display. Once the stimulus display had been on the screen for 2 s, a numeric scale from 0 to 10 was superimposed to the right of the display. Participants used a mouse to move a red dot vertically up and down the screen and align it with the number that corresponded to their chosen rating. It was stressed that only integer values were recorded by the computer. In the modal case, the numeric scale was preceded by the four color options, and participants indicated their choice by aligning the red dot to the appropriate choice.

Each stimulus was presented three times, resulting in a total of  $2$  (modal/amodal)  $\times$   $4$  (separation)  $\times$   $3$  (background color)  $\times$   $3$  (repetitions) = 72 rating trials per subject.



**FIG. 14.** The results of Experiment 1 involving a rating task on displays shown in Fig. 12. Overall completion-strength ratings decrease with increasing vertical separation between the two sets of gratings. More importantly, the modal ratings depend critically on the surround luminance, whereas amodal ratings do not.

### Results and Discussion

The averaged rating data for the 19 subjects are shown in Fig. 14. Error bars on this and all subsequent graphs represent standard errors. Not surprisingly, increasing the separation between the two circular gratings led to overall weaker ratings of completion strength.<sup>2</sup> More importantly, however, the sign of disparity had a substantial effect in modulating completion strength, with lower overall ratings for the modal case. As Fig. 14 shows, this effect is carried almost entirely by the intermediate-background case. This is clear from the fact that the *modal* ratings for the intermediate background are consistently low (relative to the dark and light backgrounds), but the *amodal* ratings for the intermediate background are similar to those in the dark and light backgrounds. Whereas the patterns of decline in ratings are quite similar for the modal and amodal conditions when the background is either dark or light, they are very different when the background has intermediate color. Thus, whereas the pattern of decline in ratings is minimally affected by the background luminance in the amodal case, it is modulated strongly by background luminance in the modal case.

These data confirm the asymmetry in the phenomenology associated with the modal and amodal versions of these displays: Whereas the percept of *amodal* completion is essentially independent of the luminance in the surrounding region, the percept of *modal* completion depends critically on surround luminance. This dependence manifests itself in two ways. First, a co-

<sup>2</sup> At the request of the action editor (G. Loftus), all inferential statistics have been removed from the text. All of the differences discussed as such in the text were found to be statistically reliable.

herent modal percept is obtained only when the luminance of the surrounding region lies outside (or equal to) the luminance range of the square-wave gratings—so that the display is consistent with camouflage and/or transparency. Second, the modal percepts associated with the light and dark surrounds are strikingly different from each other. When the surround is dark, only the dark portions of the gratings complete across the gap between the disks, resulting in the percept of dark stripes floating in front of light-colored disks. However, when the surround is light, it is the light portions of the gratings that complete, resulting in the percept of a light stripes floating in front of dark-colored disks. In contradistinction, a coherent amodal percept is obtained in all luminance regimes, and this percept is independent of the color of the surround—in each case, it consists of a single striped surface (of uniform depth) seen through two circular windows.

Although the data of this experiment clearly demonstrate a striking asymmetry in the luminance dependence of modal and amodal completion, it is possible that this difference arose because observers were focused on the surface properties of these displays rather than on the interpolated contours. Indeed, observers were required to report the color of the modally completed stripe, so if contour completion was occurring without generating any visible surface color, observers would still presumably report that no completion occurred. In order to assess whether there was an identity at the boundary level representations, we performed a discrimination task that required observers to determine whether the contours in the top and bottom figure were aligned. This task requires no explicit use of surface level representations and has been the main kind of method used to assess the similarity of modal and amodal completion. The main difference between our study and those used previously is that we explored the role of surround luminance. It has been claimed that the boundary completion process is “color-blind” (Yin, Kellman, & Shipley, 1997) so no dependence on surround luminance would be expected in this task if a common contour completion process operated in modal and amodal completion. However, if any differences between modal and amodal completion *are* observed in a discrimination task of this kind, it would provide strong evidence against the common mechanism hypothesis, even at the level of boundary and contour representations.

## EXPERIMENT 2

The aim of Experiment 2 was to test whether the differences in perceptual completion observed in Experiment 1 would manifest themselves in a discrimination task which requires subjects to judge the relative alignment of the two gratings. If so, this would provide an independent method for documenting differences in modal and amodal completion that does not rely on subjective rating scales. It also allows us to determine whether there are differences in the mechanisms underlying modal and amodal boundary com-

pletion, since in principle, the alignment task could be performed solely on the basis of the contours in the display.

## Methods

*Observers.* Seventeen subjects participated in the experiment. All had participated in Experiment 1.

*Stimuli and apparatus.* All stimulus dimensions and attributes were the same as those in Experiment 1, except for the following: (a) the horizontal misalignment (phase offset) between the two gratings was manipulated rather than the vertical separation between them and (b) only two background luminances were used ("light" and "midgray").

*Design.* Three independent variables were manipulated: the sign of the disparity given to the gratings relative to the circular boundaries (+22.86 and -22.86 min arc), the misalignment between the two gratings (6.528, 9.792, 13.056, and 16.32 min arc), and the luminance of the background ("light" and "midgray"). The vertical separation between the gratings was fixed at 2.73°.

Only the gratings within the circular boundaries were misaligned—not the circular boundaries themselves—and the task required subjects to judge the alignment of the gratings. The four levels of misalignment corresponded to phase offsets of 0.16, 0.24, 0.32, and  $0.4\pi$  (or to horizontal shifts of 0.08, 0.12, 0.16, and  $0.2P$ , where  $P$  = period of gratings). The dependent measure was the accuracy in a two-interval forced-choice (2IFC) task involving the discrimination of misalignment (described below).

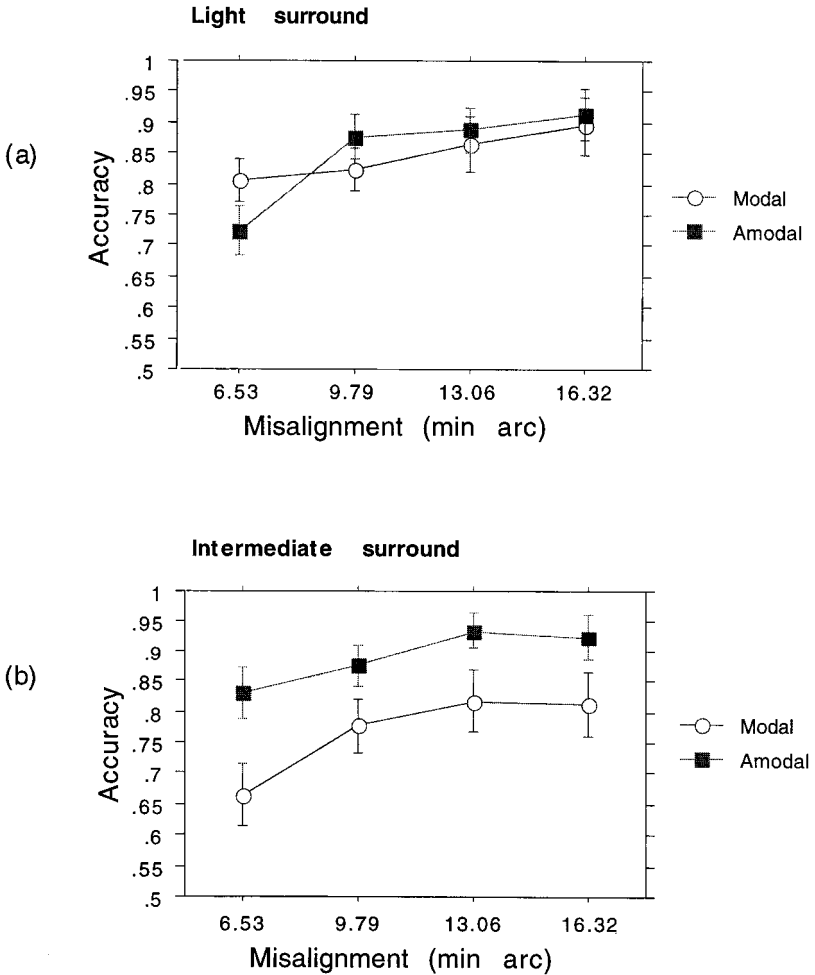
*Procedure.* As in Experiment 1, the modal and amodal conditions were run in separate blocks, and the ordering of these blocks was randomized across subjects. Each 2IFC trial consisted of a fixation cross presented for 1 s, followed by two presentations of displays like Fig. 15, each followed by a mask. The displays were presented for 750 ms each. The mask following the first display was presented for 500 ms; the one following the second display was on until subjects responded. Both masks consisted of vertically oriented rectangles with randomly assigned luminance values. The width of these rectangles equaled the half-period of the square-wave gratings, and their height equaled the radius of the circular disks. These dimensions were chosen so that the masks would have spatial structure similar to the stimuli and thus be maximally effective as masks.

On one of the two presentations, the gratings within the two circular boundaries were slightly misaligned with each other; on the other, they were perfectly aligned. The misalignments were created by shifting the grating embedded in the bottom disk horizontally relative to the grating embedded in the top disk. The direction of this shift (left/right) was determined at random from trial to trial. The observers' task was to indicate which of the two presentations, first or second, contained the misaligned gratings, by pressing "1" or "2" on the keyboard. The misalignment was equally likely to occur in either presentation interval.

Each stimulus was repeated 10 times, resulting in a total of  $2$  (modal/amodal)  $\times$   $4$  (magnitude of misalignment)  $\times$   $2$  (background color)  $\times$   $10$  (repetitions) = 160 trials per subject.

## Results and Discussion

The mean accuracy data from the 17 subjects are shown in Figs. 15a and 15b. These graphs reveal that discrimination performance in the contour alignment task was essentially identical when the surround luminance was light (and consistent with camouflage; Fig. 15a). This essentially replicates the results previously reported by Ringach and Shapley (1996). However, when the surround luminance fell between the luminance values of the grating, discrimination accuracy was substantially worse for the modal displays



**FIG. 15.** The results of Experiment 2. For the light surround, shown in a, the modal and amodal performances are essentially identical. However, for the intermediate surround (b) the amodal performance is substantially better than the modal case.

when compared to the amodal displays (Fig. 15b). Thus, the identity in modal and amodal completion performance only holds for a specific set of luminance regimes, casting doubt on the claim that contour completion processes are "color-blind."

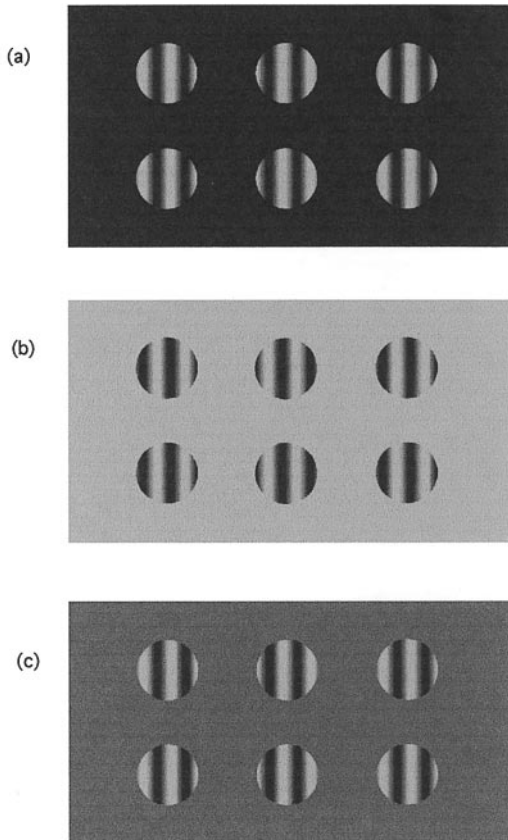
One possible explanation of the pattern of results shown in Fig. 15 is the difference in junction structure of the two kinds of displays. When the surround luminance is light, it matches the luminance of the gratings' maxima. This causes the intersections of the grating with the background to form L-

junctions. In contrast, when the surround luminance is gray, the intersections of the grating and the background form T-junctions. Thus, it is possible that the different effects of the light and intermediate surround luminances may be due to the difference in junction structure present in these images rather than a difference in the completion processes *per se*. This suggests the possibility that the different dependencies of modal and amodal discrimination judgments on surround luminance might be eliminated if the junction structure was made more similar. The purpose of Experiment 3 was to test this hypothesis.

### EXPERIMENT 3

In order to minimize the differences in the junction structure generated by the stimuli used in Experiments 1 and 2, we exploited a pattern previously used by one of us (Anderson, 1999) to investigate the computation of transparency in stereopsis (Figure 16). These images are identical to those depicted in Fig. 12, except that the square-wave grating has been replaced by a sine-wave grating. The advantage of this stimulus is that it contains contrast modulations along the entire length of the aperture boundaries. Thus, when the surround luminance is changed, there are no abrupt transitions in the junction structure generated along the aperture boundaries, as was the case in the previous experiment. However, the same qualitative transformations in surface structure are observed in this figure and in the square-wave grating pattern. In particular, when the sine-wave grating appeared behind the aperture boundaries, it appeared to complete amodally and form a single, opaque surface behind the two circular apertures. This percept occurred for all luminance values of the adjacent surround. However, when the depth relationships were reversed, the surround luminance was once again critical. When the surround was light gray, the gratings appeared to split into two layers: two distant, dark gray disks; and a set of fuzzy, light gray stripes that appeared to partially occlude these disks and complete modally across the boundaries of the dark gray disks. In this configuration, the light gray stripes were coincident with the maxima of the luminance gratings. When the adjacent surround was changed to dark gray, the gratings again appeared to split into two surfaces separated in depth. But in this luminance condition, these gratings appeared as two distant *light gray* disks that were partially occluded by a series of fuzzy *dark* stripes that modally completed across the boundaries of the white disks. In this luminance condition, the interpolated (dark) stripes were coincident with the luminance minima of the grating pattern. Importantly, when the luminance of the surround was a gray that fell between the extrema of the grating, the percept of these displays was unstable, and no modal completion was observed (see Fig. 16c).

Thus, these sine-wave grating stimuli evoke clear differences in the perceived surface structure in the modal and amodal percepts, much like the



**FIG. 16.** The stereoscopic stimuli used in Experiments 3 and 4. These are similar to the stimuli used in Experiments 1 and 2 (see Fig. 12), except that they have sinusoidal gratings rather than square-wave gratings. These displays exhibit the same asymmetries between modal and amodal completion as Fig. 12, hence showing these asymmetries are not restricted to displays with sharp contours.

square-wave patterns. However, these displays have the advantage that there are contrast signals along the entire length of the aperture boundaries, except for the isolated points along the contours where the grating luminance exactly equals the luminance of the surround. If the difference in junction structure present in the square-wave displays was responsible for the observed effects of surround luminance, then this effect should be weakened or abolished by using sine-wave grating patterns that do not contain these large differences in junction structure.

To assess this possibility, we replicated Experiments 1 and 2 using sine-wave gratings.

## Methods

**Observers.** Twenty-four subjects participated in the experiment. They were recruited from within the MIT community and were paid for their participation. All were naive to the purpose of the experiment and had normal or corrected-to-normal vision. None of these observers participated in the previous experiments.

**Stimuli.** The stimuli were identical to the ones in Experiment 1 except that the square-wave gratings were replaced with sine-wave gratings (see Fig. 16).

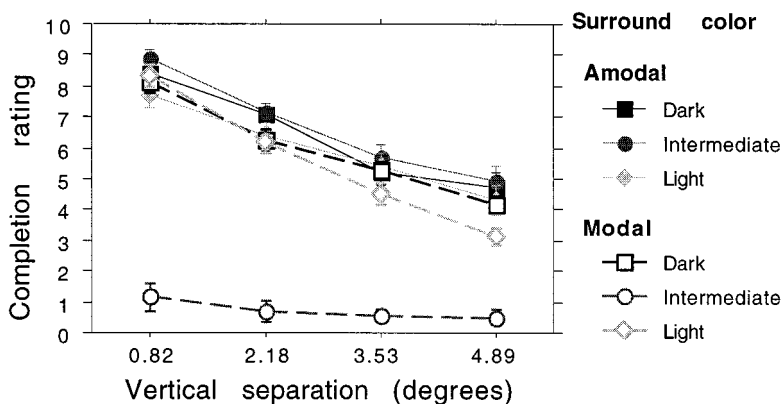
**Design.** The same three independent variables were manipulated as in Experiment 1 (the sign of relative disparity given to the gratings, the vertical separation between the two sets of gratings, and the luminance of the background), and the same levels of these variables were used. The dependent measure was the rating of completion strength given by the participants.

**Procedure.** Subjects were first given the same stereoscopic test as in Experiment 1 (one observer was excluded on this basis) and then acquainted with the phenomena of modal and amodal completion. As before, the modal and amodal trials were run in separate blocks. In the modal block, subjects reported the color of the spreading and then rated the strength with which the gratings appeared to complete across the gap. In the amodal block, they rated the strength of perceived unity between the two sets of gratings. The instructions given to the subjects, and the structure of each trial, were identical to those in Experiment 2.

As in Experiment 1, each stimulus was presented three times, resulting in a total of  $2$  (modal/amodal)  $\times 4$  (separation)  $\times 3$  (background color)  $\times 3$  (repetitions) = 72 rating trials per subject.

## Results and Discussion

The averaged rating data for the 24 participants are shown in Fig. 17. The qualitative pattern of results is virtually identical to Experiment 1. Again, increasing the separation between the two circular gratings led to overall weaker ratings of completion strength, and the sign of disparity (i.e., modal vs amodal) had a substantial effect on rated completion strength. As Fig. 17 shows, this effect is carried almost entirely by the intermediate-background



**FIG. 17.** The results of Experiment 3 involving a rating task on displays shown in Fig. 16. Overall completion-strength ratings decrease with increasing vertical separation between the two sets of gratings. As in Experiment 1, the modal ratings depend critically on the surround luminance, whereas amodal ratings do not.

condition. This is clear from the fact that the *modal* ratings for the intermediate background are consistently low (relative to the dark and light backgrounds), but the *amodal* ratings for the intermediate background are similar to those in the dark and light backgrounds. Thus, whereas the patterns of decline in ratings are quite similar for the modal and amodal conditions when the background is either dark or light, they are very different when the background has intermediate color.

These data confirm the asymmetry in the phenomenology associated with the modal and amodal versions of these displays: Whereas the percept of *amodal* completion is quite independent of the luminance in the surrounding region, the percept of *modal* completion depends critically on surround luminance.

## EXPERIMENT 4

Experiment 4 replicated the discrimination methodology used in Experiment 2, but now used sine-wave gratings instead of the square-wave gratings used in Experiment 2.

### *Methods*

*Observers.* The same 24 subjects participated as in Experiment 3.

*Stimuli and apparatus.* The stimuli were identical to the ones in Experiment 2 except in one respect, namely sine-wave gratings were used instead of square-wave gratings (see Fig. 16).

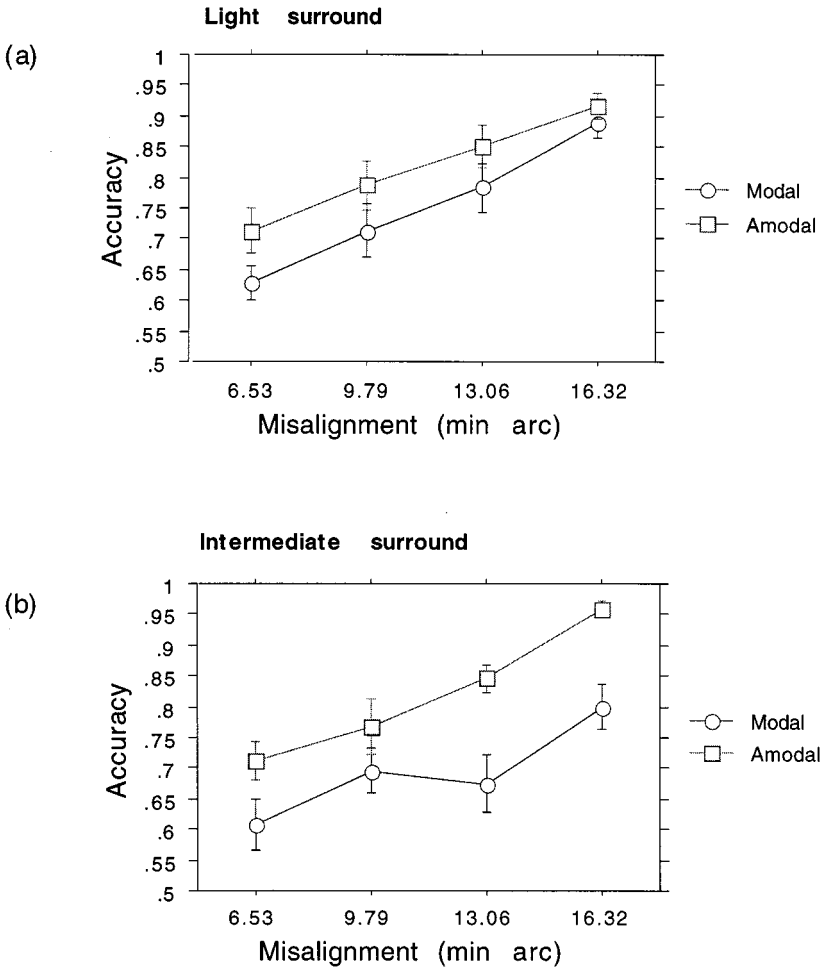
*Design.* The same three independent variables were manipulated as in Experiment 2 (the sign of the disparity given to the gratings relative to the circular boundaries, the misalignment between the two gratings, and the luminance of the background), and the same levels of these variables were used. In particular, as in Experiment 2, only the light and intermediate backgrounds were used. The dependent measure was the accuracy in a 2IFC task involving the discrimination of alignment.

*Procedure.* As in Experiment 2, the modal and amodal conditions were run in separate blocks. Each 2IFC trial was structured in the same way as Experiment 2, and the subjects' task was to indicate which of the two presentations contained the misaligned gratings.

As before, each stimulus was repeated 10 times, resulting in a total of  $2$  (modal/amodal)  $\times$   $4$  (magnitude of misalignment)  $\times$   $2$  (background color)  $\times$   $10$  (repetitions) = 160 trials per subject.

### *Results and Discussion*

The mean accuracy data from the 24 subjects are shown in Fig. 18. It can be seen that discrimination accuracy was consistently better in the amodal case than in the modal case for both intermediate *and* light surround luminances (Fig. 18). The large advantage of the amodal condition is expected for the intermediate background, since completion occurs in the amodal case but not in the modal case. However, the observed difference between the modal and the amodal case was not expected for the light background condition. There are a number of possible explanations for this finding. One possi-



**FIG. 18.** The results of Experiment 4. In both conditions, performance is better for the amodal case than the modal case, although this effect is considerably larger with the intermediate surround.

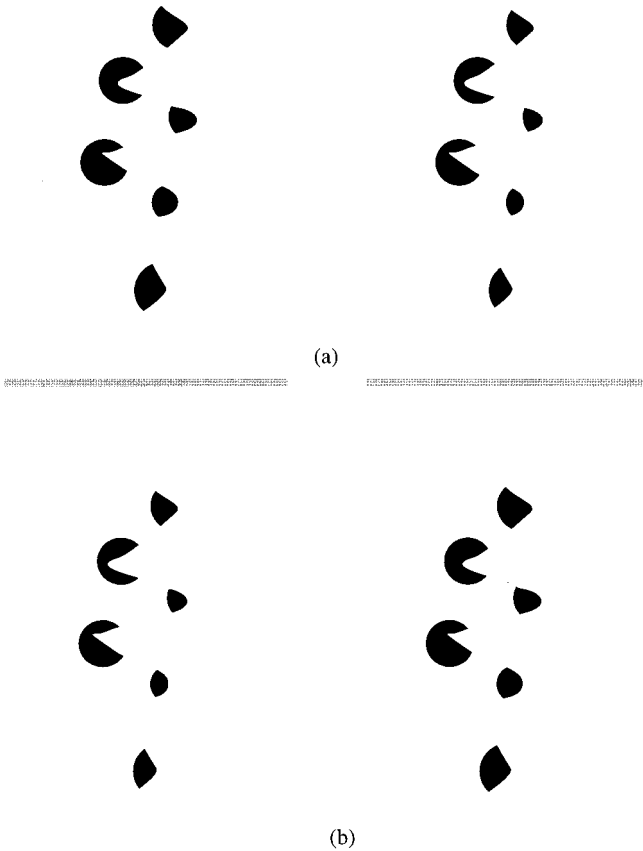
bility is that the modal percept in these displays is more complex than those that arise with square-wave gratings. In the square-wave displays, the stable modal percept involved a simple occlusion relationship, whereas the sine-wave pattern generates a percept of haze that varies in opacity (see Fig. 16; cf. Anderson, 1999). The computation of relative opacity involves a rather complex dissociation of depth and lightness, which may limit discrimination performance. Alternatively, the small advantage of the amodal condition for the light background may reflect the fact that in the modal case, only a portion of the grating perceptually completes across the gap, whereas in the amodal

configuration, the entire grating completes and forms a single unified surface. Hence, whereas misalignment judgments can be made on the basis of just portions of the grating in the modal display, the amodal discrimination could be performed on the basis of the entire grating, potentially providing redundant information that could be used to perform the discrimination.

### ASYMMETRIES IN THE SHAPES OF MODAL AND AMODAL BOUNDARIES

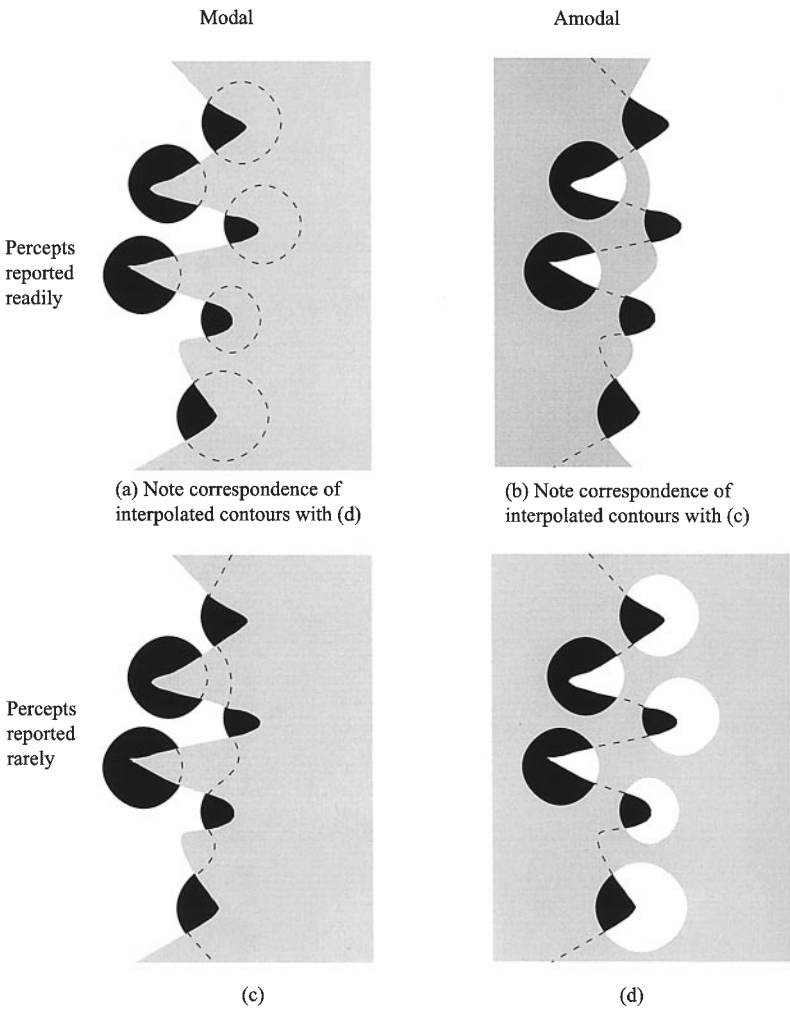
The experiments reported above provide strong evidence that modal and amodal contour and surface completion entail different dependencies on depth and luminance relationships. However, to our knowledge, there have been no previous demonstrations where the shift between a modally and an amodally completed display leads to a difference in the *shapes* of the interpolated contours. Nonetheless, there is some evidence that suggests that it should be possible to generate such displays. One of the earliest dissociations between modal and amodal contour formation was discussed by Petter (1956) and subsequently investigated by others (Tommasi, Bressan, & Vallortigara, 1995; Singh, Hoffman, & Albert, 1999). Petter generated a number of chromatically homogeneous displays which contained contours that intersected to form L-junctions (such as the SSOs discussed above). Such patterns often split into the appearance of two surfaces, but in so doing, an ambiguity in depth ordering of the surfaces is generated. Petter noticed that when confronted with this ambiguity, the visual system exhibited a bias for the shorter contour segments to appear as the modal contours. This bias is now known as ‘‘Petter’s rule.’’ The bias for shorter interpolated contours to appear as modal provides some suggestive evidence that there may be differences in the distance dependence of the mechanisms underlying modal and amodal completion. In particular, it suggests the possibility that amodally completed contours may be capable of spanning larger distances than modally completed contours. If this is true, then it should be possible to generate images that give rise to different completed contours in the modal and amodal variants of these images.

To test this hypothesis, we generated the images depicted in Fig. 19. As with the other figures presented in this article, stereoscopic depth was introduced to manipulate the relative depth of the visible contour segments in this image. The exact same two images are used to create both the modal and amodal versions of the display; relative depth is inverted by simply interchanging the two eyes’ views. The percepts reported by observers are illustrated schematically in Fig. 20. In one depth configuration (cross fusing the top two images in Fig. 19), the occluding figure appeared as a wavy edge that occluded a bipartite colored black and white background. The figure-ground relationships of the far surface oscillated over time and over observers, as predicted by the contrast depth asymmetry principle (since the border



**FIG. 19.** The “serrated edge” illusion used in Experiment 5. These displays provide an example where the modal and amodal variants differ not only in perceived surface structure, but also in the shapes of the interpolated contours. When a is viewed through a stereoscope (uncrossed fusion), the resulting percept consists of six circular disks that are partly occluded by a jagged white surface on the right (a schematic of this percept is shown in Fig. 20a). By contrast, when the sign of disparity is inverted, the modal completion of these four black blobs tends to take the form of a single wavy contour that runs vertically down the center of the display (a schematic of this percept is shown in Fig. 20b). The depth relations are reversed for crossed fusion.

ownership of the more distant contour is inherently ambiguous, and there is no information to bias one side to be interpreted as figure more than the other). When the depth relationships were reversed, however, observers reported that a white surface appeared to occlude five black disks lying on a white background. *Note that the interpolated contours are very different in these two percepts:* in the first case, the curved contour segments bordering the black inducing elements appear to join into a continuous, wavy contour;



**FIG. 20.** Schematic representation of the percepts associated with the stereoscopic displays in Fig. 19. Dashed lines represent amodally completed contours. (a) The predominant percept associated with Fig. 19b when cross-fused (reported by all 21 subjects in Experiment 5); (b) the predominant percept associated with Fig. 19a when cross-fused (reported by 19 of the 21 subjects). (c and d) The alternative percepts of Figs. 19a and 19b, respectively, which were rarely reported.

in the latter, these same curved contour segments were reported to form unconnected black disks. Thus, this example provides evidence that the structure of the interpolated contour can be altered by shifting the relative depth of the inducing elements, which in turn determines whether a contour appears to complete modally or amodally.

In order to provide more objective data demonstrating the difference between these two percepts, we performed an experiment that required observers to report either the number of holes or the number of disks present in these two displays.

## EXPERIMENT 5

### *Methods*

*Observers.* Twenty-one naive observers participated in the experiment. They were recruited from within the MIT community and were paid for their participation. All were naive to the purpose of the experiment, and had normal or corrected-to-normal vision. All observers also participated in Experiments 3 and 4.

*Stimuli.* The stimuli consisted of the two stereoscopic displays shown in Fig. 19. These displays were presented on a high-resolution ( $1600 \times 1200$ ) Mitsubishi Diamond Pro 91TXM monitor and viewed through a mirror stereoscope at a distance of  $\sim 99$  cm.

*Procedure.* Observers were shown the two displays through a stereoscope, with the order of presentation randomized. For the display in which the circular contours are given far disparity (Fig. 19a), observers were asked to report the number of circular disks they perceived in the display. For the display in which the circular contours are given near disparity, observers were asked to report the number of circular windows they perceived. From the observer's response ("2" or "6"), we inferred whether they perceived the left contours of the four black regions completing into four separate circles, or into a single wavy contour.

### *Results and Discussion*

All observer responses were either "2" or "6" holes or disks present in the displays. For the display in which the circular contours need to be amodally completed (Fig. 19b, cross-fused), all 21 observers (100%) reported perceiving 6 circular disks, partly hidden behind a jagged white surface. However, for the display in which the circular contours need to be modally completed (Fig. 19a, cross-fused), only 2 of the 21 observers (9.52%) reported perceiving 6 circular windows. Most observers, therefore, had the percept of 2 circular windows on the left and a single wavy occluding edge running down the center of the display. In a follow-up question, observers were explicitly given the choice between the 2 possible modal completions to verify their experience of the contour depicted in Fig. 19b. In particular, they were asked whether the four vertically aligned black regions induced four separate circular windows or whether it appeared predominantly as a single wavy occluding edge. Only 1 of the 21 observers (4.76%) chose the four-windows option as a better description of their percept.

These displays thus provide a clear example in which the switch in relative

depth and the accompanying transition of a contour from modal to amodal appearance causes a change in the shape of the completed contours that are perceived, not simply a change in the depth placement of an identically shaped contour.

## GENERAL DISCUSSION

The results of the experiments described above provide new and strong evidence challenging the thesis that modal and amodal completion are driven by a common mechanism. The results of both our rating experiments and the discrimination experiments reveal striking asymmetries in these two forms of completion. When contoured displays were used (Experiment 2), no differences in discrimination accuracy were observed between the modal and amodal targets when the background was light (and the conditions for camouflage are satisfied). This essentially replicates previous findings supporting the identity hypothesis (Kellman & Shipley, 1991; Shipley & Kellman, 1992; Ringach & Shapley, 1996). However, when the surround luminance fell between the extrema of the grating patterns, the conditions for camouflage were violated, and substantial differences in discrimination accuracy between the modal and amodal displays were observed. These differences cannot be attributed to a difference in junction structure used to create the two kinds of displays, since the junction structure was identical for both the modal and amodal display types. Moreover, when the junction structures were more nearly equated for the light and intermediate surround cases (by using sine-wave gratings instead of square-wave gratings), differences in discrimination accuracy were observed for both light and intermediate surrounds. Finally, we demonstrated that differences in the shapes of modally and amodally completed targets could also be observed, providing a critical counterexample to the claim of a common boundary completion process. Taken together, these results cast strong doubts on the claim that a single mechanism underlies both modal and amodal completion.

One possible argument that might be presented to sustain the identity hypothesis is to claim that the differences we observed between the modal and amodal conditions were based on differences at surface level representations, not mechanisms of contour completion. In principle, an argument of this kind would allow the common mechanism thesis to be sustained at the level of contour representations, preserving at least the weaker version of the identity hypothesis. There are a number of problems with this line of reasoning. First, with regard to our rating and discrimination experiments, we were careful to develop methods that were virtually identical to those that have produced data that have been used to uphold the identity hypothesis. If our experiments do not bear on the identity hypothesis at contour level representations, then the same critique applies to all previous research that has argued

that such experimental methods can be used to *support* the common mechanism thesis at the level of boundary interpolation. One cannot propose that a failure to observe a difference between modal and amodal completion (a negative result) provides evidence supporting the common mechanism thesis and subsequently argue that a virtually identical method that reveals substantial differences in the two forms of completion does not impact on the contour hypothesis. Indeed, our contour discrimination methodology was employed precisely so that performance could be based solely on contour completion mechanisms, yet we nonetheless observed significant differences in the modal and amodal conditions. Second, the results of Experiment 5 reveal that the modal–amodal shift can cause significant changes in the shapes of interpolated contours. Shipley & Kellman (1992) explicitly state that the identity hypothesis “. . . would be unavailable if the units in the array or the shapes of interpolated boundaries changed when the modal–amodal switch occurred. Such changes do not appear to occur” (p. 117). The results of Experiment 5 demonstrate that this claim is simply false, and hence, by their own stated criteria, the identity hypothesis is now “unavailable.” Finally, the only physiological evidence that can be currently brought to bear on the identity hypothesis reveals a dissociation of modal and amodal completion at the earliest stage of cortical processing where orientation information is explicitly represented (Sugita, 1999; Peterhans & von der Heydt (1989). Although the von der Heydt and Peterhans study left open the possibility that cells in V1 might process modal and amodal contours with common mechanisms, the results reported by Sugita provide evidence against this view.

In sum, both the psychophysical data reported herein and the extant physiological data suggest that modal and amodal contours are distinguished at the earliest stages of visual processing where orientation information is made explicit. Perhaps most importantly, the results of Experiment 5 demonstrate that the shapes of completed contours can change during the modal–amodal transition, providing direct evidence that there is more to the modal–amodal shift than the placement of completed contours in depth. Rather, the change in relative depth can induce differences in the shapes of the contours that are generated by completion mechanisms, in direct opposition to the claims of Kellman and Shipley (1991; Shipley & Kellman, 1992).

Finally, theoretical considerations about the relationship between image contrast and perceived depth reveals that there are inherent differences in the role of relatively near and far image contrasts in specifying surface structure (the contrast depth asymmetry principle). These theoretical considerations, together with a host of phenomenological demonstrations, reveal that relative depth strongly constrains what features participate in the completion process. This principle makes it clear why relative depth can dramatically alter *what* participates in a completion process, which in turn constrains what is actually interpolated. Thus, modal and amodal completion cannot be

driven by a common mechanism because modal and amodal completion involve different relative depth orderings and are therefore subject to the asymmetric constraints on relative depth imposed by the contrast depth asymmetry principle.

In conclusion, the results reported herein provide evidence that the modal–amodal dichotomy does not simply reflect differences in the phenomenal appearance of completed contours, surfaces, and objects, but also reflects the operation of distinct neural mechanisms at the earliest stages of cortical processing. There appear to be two fundamental reasons for the differentiation of mechanism at such an early stage of processing. First, the contrast depth asymmetry principle expresses an inescapable constraint on the relationship between image contrast and relative depth, which determines the elements that participate in the completion process. Second, the environmental conditions that give rise to camouflage are much more restricted than those that give rise to partial occlusion, and the visual system appears to have developed separate mechanisms to overcome these two sources of image fragmentation. Although it is likely that there are regimes in which the geometric constraints on modal and amodal contour completion are similar, this does not imply that the two forms of completion share a common mechanism. We are forced to conclude that the studies that have found an identity to hold between modally and amodally completed contours represent special cases in which the two forms of completion exhibit similar properties and do not represent the operation of a common underlying mechanism.

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(Accepted June 11, 2001; published online September 6, 2001)