Perception, 2002, volume 31, pages 531 – 552

DOI:10.1068/p3363

Perceptual assignment of opacity to translucent surfaces: The role of image blur

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Received 20 June 2000, in revised form 19 June 2001

Abstract. In constructing the percept of transparency, the visual system must decompose the light intensity at each image location into two components—one for the partially transmissive surface, the other for the underlying surface seen through it. Theories of perceptual transparency have typically assumed that this decomposition is defined quantitatively in terms of the inverse of some physical model (typically, Metelli's 'episcotister model'). In previous work, we demonstrated that the visual system uses Michelson contrast as a critical image variable in assigning transmittance to transparent surfaces—not luminance differences as predicted by Metelli's model [F Metelli, 1974 *Scientific American* **230**(4) 90 – 98]. In this paper, we study the contribution of another variable in determining perceived transmittance, namely, the image blur introduced by the light-scattering properties of translucent surfaces and materials. Experiment 1 demonstrates that increasing the degree of blur in the region of transparency leads to a lowering in perceived transmittance, even if Michelson contrast remains constant in this region. Experiment 2 tests how this addition of blur affects apparent contrast in the absence of perceived transparency. The results demonstrate that, although introducing blur leads to a lowering in apparent contrast, the magnitude of this decrease is relatively small, and not sufficient to explain the decrease in perceived transmittance observed in experiment 1. The visual system thus takes the presence of blur in the region of transparency as an additional image cue in assigning transmittance to partially transmissive surfaces.

1 Introduction

In constructing the percept of transparency—seeing an object or surface through a partially transmissive surface—the visual system must decompose or *scission* (Koffka 1935) the light intensity at each retinal location, and assign the separate components to distinct surfaces in depth. The contributions of the underlying surface and the transparent surface are collapsed onto a single intensity value at each point in the image, and these contributions must be separated if the two surfaces are to be extracted. In this regard, the problem of perceptual transparency is similar to other visual problems in that multiple contributions (eg surface reflectance, illumination, surface orientation) must be inferred from a single pattern of light intensities. What makes perceptual transparency unique, however, is that the image decomposition involves the visual construction of two distinct *surfaces* (or material layers) along each line of sight.

Figure 1 demonstrates the problem of transparency: The display at the left is seen as a black-and-white surface with an overlying mid-gray partially transmissive surface—even though each point in the image contains a single gray-level value. Each light-gray patch in the display is thus decomposed into a mid-gray transparent component and an underlying white component, whereas each dark-gray patch is decomposed into mid-gray and underlying black. If the same light-gray and dark-gray patches are seen in isolation (right side of figure 1), no such decomposition occurs, and each patch is seen as opaque.

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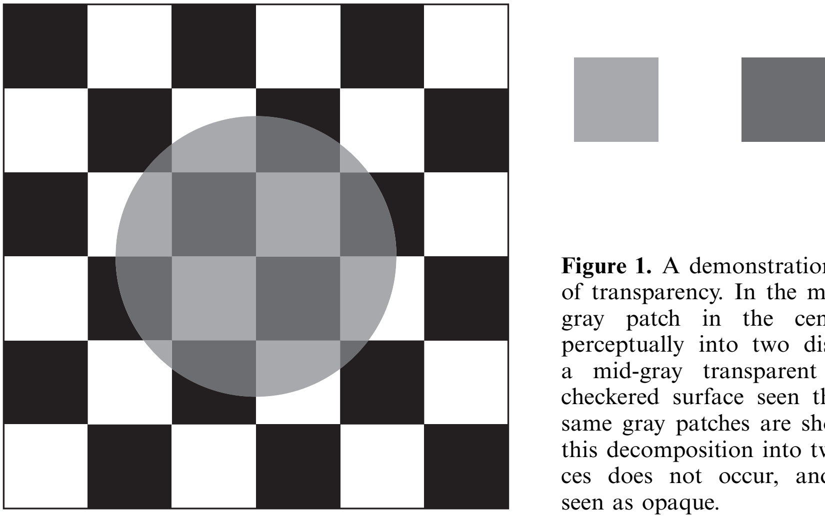
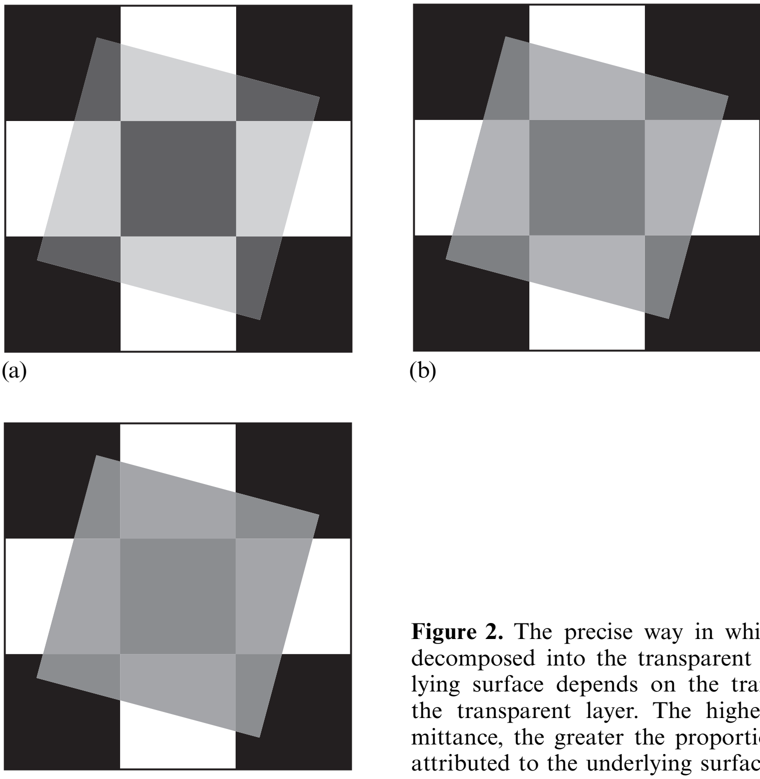


Figure 1. A demonstration of the problem of transparency. In the main display, each gray patch in the center decomposes perceptually into two distinct surfaces—a mid-gray transparent surface and a checkered surface seen through it. If the same gray patches are shown in isolation, this decomposition into two distinct surfaces does not occur, and each patch is seen as opaque.

There are two basic questions concerning the perception of transparency. (1) When does the visual system initiate the decomposition of an image region to create a percept of transparency? (2) How does it quantitatively partition image luminance into the underlying surface and the transparent surface? In addressing the first question, previous work has pointed to the role of both photometric (or luminance) and geometric (or figural) constraints (Metelli 1974; Kanizsa 1979; Beck et al 1984; Adelson and Anandan 1990; Gerbino et al 1990; Gerbino 1994; Anderson 1997, 1999; Singh and Hoffman 1998). In this paper, we focus on an important aspect of the second problem, namely, how the visual system assigns transmittance (or opacity) to the transparent layer. (Transmittance refers to the degree to which a transparent layer lets light through from underlying surfaces. Highly transmissive surfaces let a large proportion of the light through; highly opaque surfaces let very little light through.) For example, compare the three displays in figure 2. In figure 2a, the transparent layer looks quite transmissive, and most of the image luminance in the central region is attributed to the underlying surface. In figure 2c, however, the transparent layer looks quite opaque, and most of the image luminance in the central region is now attributed to the transparent layer. The problem of partitioning image luminance into two surfaces in depth is thus intimately related to the problem of assigning transmittance to the transparent surface: the higher the transmittance assigned to the transparent surface, the greater is the proportion of image luminance attributed to the underlying surface.

Most work on perceptual transparency has either assumed or argued that perceptual decomposition in transparency is carried out in a way that is consistent with the physical (or generative) equations that describe Metelli's episcotister model of transparency (Metelli 1970, 1974a, 1974b, 1985; Metelli et al 1985). However, we have recently demonstrated (Singh and Anderson 2002) that the perceived surface attributes of a transparent surface deviate systematically from the solutions derived from Metelli's equations. In particular, in assigning transmittance to a transparent surface, the visual system uses the Michelson contrast in the region of transparency, relative to adjoining image regions, whereas Metelli's solution for α predicts transmittance to be given by relative luminance differences. Moreover, in estimating the lightness of a transparent surface, the visual system is biased strongly toward the mean luminance in the region of transparency, and is thus able to separate and 'discount' only to a partial extent the contributions of the underlying surface. These results indicate that perceptual scission in transparency is not the inverse of the equations of 'color fusion' described by Metelli



(a) (b) (c)

Figure 2. The precise way in which image luminance is decomposed into the transparent surface and the underlying surface depends on the transmittance assigned to the transparent layer. The higher the perceived transmittance, the greater the proportion of image luminance attributed to the underlying surface.

(see section 2). Rather, the visual system appears to track certain simple, but critical, image variables in order to assign surface attributes to transparent layers. This suggests that the study of perceptual transparency must be aimed at identifying such image variables and their perceptual contributions, rather than simply equating perceptual theory with the inverse of specific generative models.

In this paper, we demonstrate that image blur is an additional variable that the visual system uses to assign transmittance to partially transmissive layers. Previous work on perceptual transparency (including our own) has typically studied contexts in which the partially transmissive layer transmits some of the incident light, and reflects some of it. Many partially transmissive materials, however, also exhibit the property of translucency, which leads to a blurring of contours seen through the translucent material. Here, we study the perceptual consequences of such blurring. Our results show that the visual system takes the presence of blur in the region of transparency (relative to adjoining regions) as evidence for a decrease in the transmittance of a transparent layer, even if the Michelson contrast remains unchanged in this region. Moreover, this decrease in perceived transmittance is not accounted for by the relatively small decrease in apparent contrast that results from such blurring. Hence, the visual system takes the presence of blur as a further image cue—in addition to contrast reduction—in assigning transmittance to partially transmissive surfaces.

We begin with a short exposition of Metelli's episcotister model, and the predictions it makes regarding perceived surface attributes. We briefly review empirical work aimed at testing the predictions of Metelli's model, including our own previous results that demonstrate the critical role of Michelson contrast in assigning perceived transmittance. We then turn to the perceptual contributions of image blur in determining perceived transmittance.

2 Metelli's equations and their extensions

Metelli (1970, 1974a, 1974b, 1985; Metelli et al 1985) proposed a model of transparency based on the physical setup of an episcotister. A flat fan blade with reflectance t and an open sector of relative area α is rotated in front of a bipartite background (figure 3a). When this rotation is faster than fusion speed, it leads to the percept of a homogeneous transparent layer overlying the bipartite background (figure 3b). The term α then captures the transmittance of the episcotister, namely, the proportion of light that it lets through. Large values of α (ie values close to 1) correspond to highly transmissive episcotisters, whereas small values of α (ie close to 0) correspond to episcotisters that are almost fully opaque.

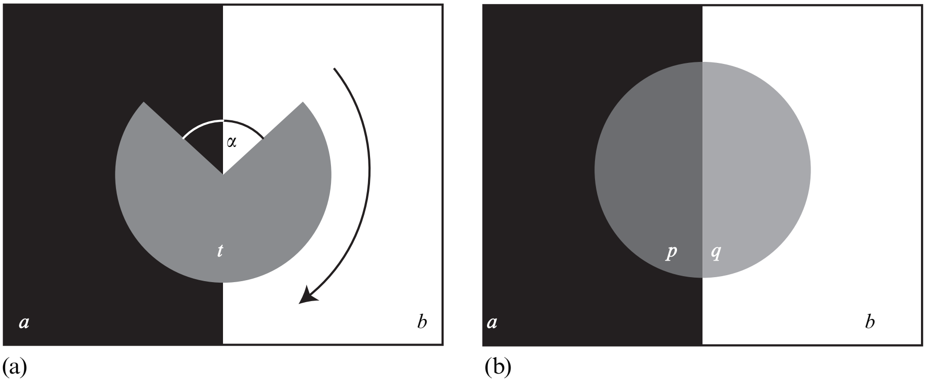


Figure 3. Metelli's episcotister model of transparency. A circular disk with an open sector is rotated rapidly in front of a bipartite background (a), hence creating a percept of transparency (b). This leads to a quantitative model of color fusion in transparency. Perceptual scission is then defined by inverting the equations of color fusion.

The resulting 'color mixing' (Metelli 1974a) in the episcotister model is described by Talbot's law:

$$p = \alpha a + (1-\alpha)t \,, \tag{1}$$

$$q = \alpha b + (1-\alpha)t \,. \tag{2}$$

In other words, reflectances a and t are mixed in ratios α and $1-\alpha$ respectively, resulting in reflectance p; and b and t are mixed in ratios α and $1-\alpha$ resulting in q. Since the terms α and t are identical in (1) and (2), these equations can be solved to yield the following solutions:

$$\alpha = \frac{p-q}{a-b} \,, \tag{3}$$

$$t = \frac{aq-bp}{a+q-b-p} \,. \tag{4}$$

Metelli argued that perceptual scission in transparency is given by the inverse of 'color fusion', and that the perceived transmittance and reflectance of the transparent layer are thus given by the solutions to equations (3) and (4). In particular, solution (3) predicts that perceived transmittance is determined by the reflectance difference in the region of transparency, relative to that in the surrounding region (see figure 3b).

Although Metelli's equations are written in terms of reflectance values, Gerbino et al (1990) have shown that the same equations are obtained when luminance is substituted for reflectance. The luminance formulation of Metelli's equations is more appropriate from the point of view of perceptual theory since the visual system is not 'given' reflectance values, but luminance values. Formally identical equations also follow in the context of a mesh (or screen) placed in front of a bipartite background, rather than a rotating episcotister. In this case, α refers to the areal density of the holes in the mesh, and t refers to the reflectance of the material portion of the mesh.

More recently, we (Singh and Anderson 2002) have extended the luminance version of Metelli's equations to textured displays that contain a continuous range of luminance values, rather than four distinct values (a, b, p, q). The local solutions for α and t in this case are given by:

$$\alpha = \frac{L_{\text{max}} - L_{\text{min}}}{A_{\text{max}} - A_{\text{min}}} = \frac{L_{\text{range}}}{A_{\text{range}}} , \tag{5}$$

$$t = \frac{A_{\text{range}} L_{\text{mean}} - A_{\text{mean}} L_{\text{range}}}{A_{\text{range}} - L_{\text{range}}} , \tag{6}$$

where L refers to luminance values in the image region containing transparency, and A refers to luminance values in image regions where the underlying surface is seen in plain view. These solutions are simple extensions of the luminance versions of solutions (3) and (4). In particular, solution (5) predicts that perceived transmittance is given by the luminance range within the region of transparency, relative to adjoining regions.

3 Perceptual validity of Metelli's model

To what extent do Metelli's equations provide an account of how the human visual system assigns surface attributes to transparent layers? Most studies of perceptual transparency have argued *for* the validity of Metelli's model. Ironically, however, Metelli himself made an observation that undermined the perceptual validity of his model. Citing an observation by Tudor-Hart (1928), Metelli (1974b) noted that a black episcotister looks more transmissive than a white episcotister of the same physical transmittance α (ie with the same sized open sector). However, Metelli never reconciled this observation with his formal model. In this section, we briefly review some of the empirical studies that have tested Metelli's model. We argue that the reason these studies have not found the failures in Metelli's model is because they have typically not measured *separately* how the visual system assigns α and t.

Gerbino et al (1990) presented observers with displays like those shown in figure 4. On each trial, all luminances in the test display (A, B, P, Q) and the background luminances in the matching display (A', B') were fixed. Observers adjusted luminances P' and Q' in the matching display [which varied together so as to keep $(P'-Q')/(A'-B') = (P-Q)/(A-B)$ so that α and α' would be equated according to the episcotister model] to make the transparent layers appear identical in the two displays. Gerbino et al tested the performance of various models in predicting observer responses. In particular, they contrasted the predictions of the episcotister model with those of other models that do not invoke the notion of scission into multiple layers—such as simultaneous contrast, and mean image luminance in the central region. On the basis of these analyses, Gerbino et al concluded that the episcotister model provides the best predictor of perceived surface attributes of a transparent layer.

More recently, Kasrai and Kingdom (2001) used six-luminance displays like that shown in figure 5 to test the predictions of the episcotister model. On each trial, they clamped all three luminances in the surround and two of the luminances in the center. Observers adjusted the third luminance in the central disk to make the disk appear as a homogeneous transparent layer. They found that observers' settings of this third luminance correlated strongly with the predictions of the episcotister model. They concluded that observers' settings of transparency are both accurate and precise—in accordance with the episcotister model.

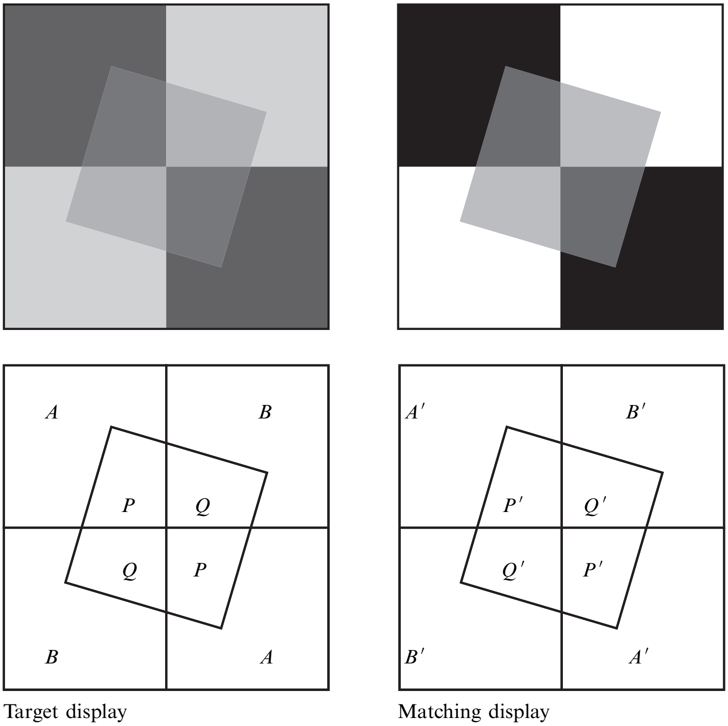


Figure 4. Displays used by Gerbino et al (1990) to test the episcotister model. All luminances in the target display (A, B, P, Q), and the background luminances in the matching display (A', B') were fixed. Observers adjusted the luminances P' and Q' to make the two transparent layers look identical.

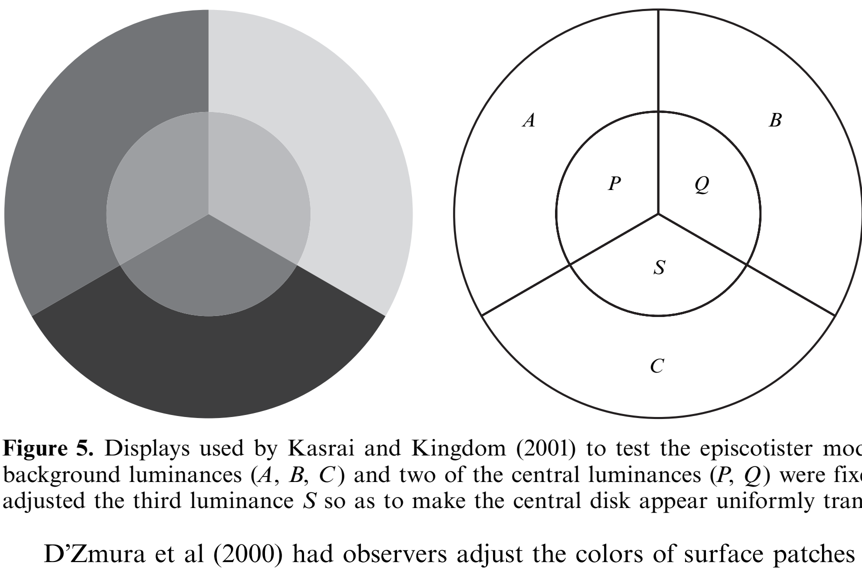


Figure 5. Displays used by Kasrai and Kingdom (2001) to test the episcotister model. The three background luminances (A, B, C) and two of the central luminances (P, Q) were fixed. Observers adjusted the third luminance S so as to make the central disk appear uniformly transparent.

D'Zmura et al (2000) had observers adjust the colors of surface patches seen behind simulated color filters so as to match the colors of corresponding surface patches seen in plain view. They found that an extension of Metelli's equations to the chromatic domain ['the convergence model' (see D'Zmura et al 1997; Chen and D'Zmura 1998)] provided as good a fit to their data as a full affine model, even though the convergence model has only four parameters compared with the twelve parameters of the full affine model. Moreover, on the basis of the fits to the convergence model, they inferred that human observers underestimate the transmittance of a transparent filter by a factor of almost two (see also Hagedorn and D'Zmura 2000).

Although the above three studies employed very different experimental techniques, they share the characteristic that they did not give observers the opportunity to make *separate* matches of the transmittance and lightness of a transparent layer. Observers' matches were based either on the overall appearance of the transparent layer, or on the appearance of underlying surfaces. As a result, these studies did not allow for a direct test of the perceptual validity of the Metelli's solutions for surface transmittance (α) and lightness (t).

Beck et al (1984) used a rating scale to study how subjects assign perceived transmittance to transparent layers. In their experiment 3, they presented subjects with three-part transparency displays like that shown in figure 6, and asked them to rate the transmittance ('degree of transparency') of the overlying layer on a scale from 0% ('nearly completely opaque') to 100% ('nearly completely transparent'). They found that subjects' ratings correlated better with values of α computed by taking ratios of lightness differences, rather than reflectance differences. In this regard, this has been one prior study that did find violations of Metelli's model. On the basis of their results, Beck et al argued that the terms a, b, p, and q in Metelli's equations should be interpreted as lightness values, rather than reflectance values. A disadvantage of doing so, however, is that it makes uninterpretable any predictions based on equation (4) for t since this solution now involves sums and products of lightness values (Beck et al 1984). Treating these terms as luminance values, on the other hand, allows perceptually meaningful constraints to be derived from equation (4) (see Singh and Anderson, in press). Moreover, treating a, b, p, and q as lightness values requires the assumption that there is an initial stage where local lightness values are computed, prior to (and largely independent of) the subsequent construction of surfaces (see Gerbino et al 1990). Finally, in their experiment 3, Beck et al used displays involving 'partial transparency' (Metelli 1974b)—an anomalous situation in which, putatively, only the region of overlap in a three-part display like figure 6 is seen as transparent. In a subsequent experiment involving 'complete transparency' (experiment 4) Beck et al found that lightness was no better than reflectance in predicting subjects' ratings of perceived transmittance. They concluded that "we do not as yet have a good understanding of the factors controlling the judgment of transparency [transmittance] with complete transparency" (page 420).

In order to obtain direct measurements of how the visual system assigns perceived transmittance, we (experiment 1 in Singh and Anderson 2002) had observers perform a matching task with stereoscopic displays that give rise to the percept of a transparent

Figure 6. A class of displays used by Beck et al (1984) to measure perceived transmittance. Subjects indicated which of the two squares appeared to be transparent, and then rated how transparent it looked on a scale from 0 ('nearly completely opaque') to 100 ('nearly completely transparent').

disk floating in front of a sinusoidal grating (figure 7 shows a schematic of the task, with monocular versions of these displays). From trial to trial, the mean luminance within the central disk of the matching display was set to different values, and observers adjusted its luminance range (ie amplitude) in order to match the perceived transmittance of a fixed target disk. Observers were asked to ignore any difference in lightness between the target and matching disks, and to base their responses solely on perceived transmittance. Our results demonstrated that observers can make reliable and consistent matches of perceived transmittance—but that these matches deviate systematically from the predictions embodied in Metelli's equations (and their simple extensions to textured displays). For example, figure 8a shows the matches of an observer to four different target disks. Whereas Metelli's equations predict that perceived transmittance should be independent of mean luminance [and depend solely on relative luminance range—see equations (3) and (5)], our results demonstrate that observers' settings of luminance range increase monotonically with the mean luminance in the matching disk. In fact, these data are fit almost perfectly by linear functions with zero intercepts ($y = kx$). This pattern of results indicates that the critical variable that the visual system uses to assign perceived transmittance is Michelson contrast (rather than luminance differences or luminance range). Indeed, replotting the data in terms of Michelson contrast produces data curves that are essentially independent of mean luminance (figure 8b).

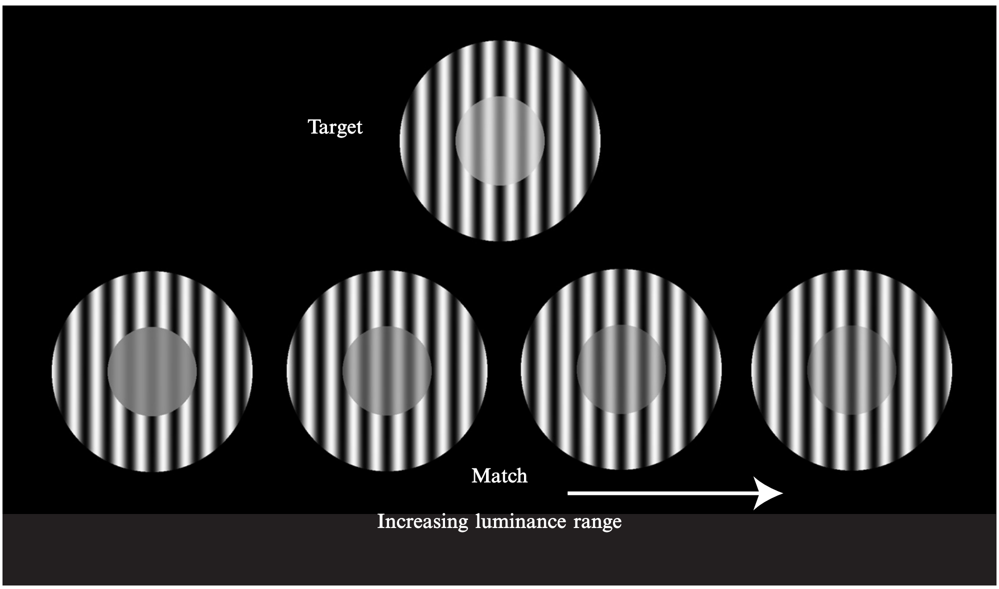


Figure 7. Displays used by Singh and Anderson (2002) to perform a transmittance-matching task (the actual stimuli were presented in stereo). The mean luminance in the central disk of the matching display was clamped at different values from trial to trial, and observers adjusted its luminance range to match the perceived transmittance of a fixed target disk. The task required observers to ignore any differences in the lightness of the disk, and base their matches solely on its perceived transmittance.

The proposal that perceived transmittance is determined by Michelson contrast accounts for Metelli's observation noted above: a black episcotister appears more transmissive than a white episcotister of the same physical transmittance because it generates a higher Michelson contrast than the white episcotister. More generally, this proposal implies that the ordinal relationship between physical and perceived transmittance depends on whether the transparent layer decreases or increases mean luminance in the region of transparency, relative to adjoining image regions. Observers systematically

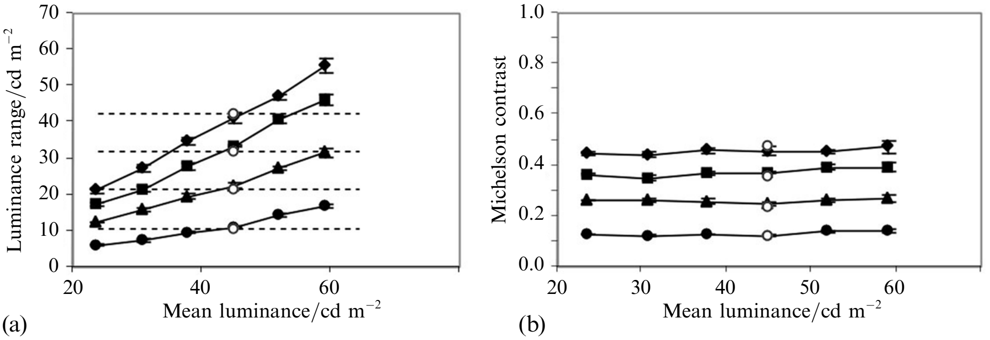


Figure 8. (a) Transmittance-matching data from observer MS, reported in Singh and Anderson (2002). Contrary to the predictions of Metelli's equations (shown in dashed lines), the transmittance matches increase linearly with the mean luminance in the matching disk. The different symbols represent matches to four different target disks. (b) Replotting the data in terms of Michelson contrast makes these curves essentially independent of mean luminance. This indicates that the visual system uses Michelson contrast to assign transmittance to transparent layers—not luminance differences or luminance range, as predicted by Metelli's model.

overestimate the transmittance of darkening transparent layers, and systematically underestimate the transmittance of lightening transparent layers.

More generally, the above result stresses the need to identify and study experimentally the critical image variables that the visual system uses to infer surface structure—rather than simply equating perceptual theory with the inverse of specific generative models. In the current paper, we study the contributions of another image variable that the visual system uses to assign transmittance to transparent layers, namely the presence of blur in the region of transparency, relative to adjoining image regions.

4 The problem of translucency

Theoretical and empirical work on perceptual transparency has focused on two main aspects of partially transmissive materials: (i) they transmit part of the light falling on them (hence attenuating the incident light); and (ii) they reflect part of the light. In Metelli's equation (1), for example, the term αa captures the transmissive component, whereas $(1-\alpha)t$ captures the reflective component. These components lead to a lowering in luminance differences (Metelli 1974a; Gerbino et al 1990) and a lowering in Michelson contrast (Singh and Anderson 2002) in the region of transparency—but do not alter the underlying contours themselves.

Another possibility occurs in the context of translucency, where the partially transmissive material disperses light in multiple directions while transmitting it. Early work in the optics of paint layers modeled translucent media as stacks of infinitesimally thin layers (Kubelka and Munk 1931; Kubelka 1954), each of which transmits some of the light forward, and reflects some of it backwards. This process repeats recursively, leading to a series of back-and-forth reflections within the translucent material. In order to derive closed-form solutions, this early work considered only scattering reflections in the 'upward' and 'downward' directions ["to avoid complicating the calculation hopelessly", see footnote 3 in Kubelka and Munk (1931)].(1) Recent work in computer graphics has developed models of light scattering in all directions, in order to render realistic-looking images of translucent materials, such as thin leaves (Blinn 1982; Hanrahan and Krueger 1993). These models capture two sources of light scattering (see figure 9a):

(1) Although this restricted type of scattering changes the light distribution through the partially transmissive material relative to Metelli's model, it does not lead to a blurring of underlying surface structure.

(i) the scattering that occurs at the surface of the material due to fine-scale irregularities in its geometry; and
(ii) subsurface volume scattering that takes place within the material due to inhomogeneities in its refractive index (as in wax or vaseline).

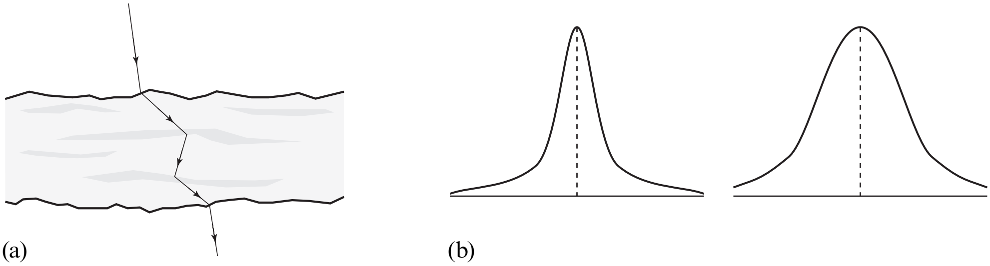


Figure 9. (a) Schematic of a model of light scattering in translucent materials, based on Hanrahan and Krueger (1993). This model takes into account (i) scattering due to fine-scale irregularities on the surface of the material, and (ii) subsurface volume scattering due to inhomogeneities within the material. (b) The overall scattering effects of a translucent layer may be captured in terms of a point-spread function that describes how the image of a point would project through the translucent layer.

Although translucent materials have been studied from the point of view of optics and computer graphics, there has been virtually no work on the *perception* of translucency. From the point of view of the visual system, the information available consists only of the overall statistical consequences of light scattering that are measurable in the resulting image—not its specific sources. Thus we may ask: what image properties does the visual system use in assigning attributes to translucent materials? Viewing an edge (or contour) through a translucent material has two main consequences. First, it leads to a blurring of the underlying contour. This effect may be captured in terms of a point-spread function that describes how the image of a 'point' would project through the translucent material. Higher degrees of scatter are captured by larger standard deviations of the point-spread function (see figure 9b). Second, the presence of a translucent layer lowers the physical contrast across the contour. We have previously noted that, even in the absence of scattering, partially transmissive materials lower the Michelson contrast across underlying contours. The presence of scattering acts as an additional source of contrast reduction. This is easily appreciated in the limit, where the degree of scattering is so high that it completely eliminates all structure in the resulting image. (Formally, a convolution with a point-spread function of sufficiently high standard deviation will result in an image with close-to-zero contrast.)

Previously, we have demonstrated that the visual system uses relative Michelson contrast as a critical image variable in assigning opacity to (non-scattering) transparent surfaces. In this paper, we study the contributions of relative image blur. As we have noted above, blur and contrast typically covary for translucent surfaces (because an increase in scatter leads both to an increase in blur and to a decrease in contrast). In order to study the contributions of blur, in experiment 1 we apply increasing levels of blur to the region of translucency—but then renormalize its amplitude so that its Michelson contrast remains unchanged. In experiment 2, we study how the blurs used in experiment 1 modulate apparent contrast in the absence of perceived transparency. Together, these experiments allow us to assess the extent to which image blur plays a role in assigning surface opacity, above and beyond the contributions of Michelson contrast and apparent contrast.(2)

(2) In the current paper, we focus on the case in which the blurring is spatially isotropic. This is a reasonable starting point since in many situations, because the light rays are scattered multiple times, their directions become essentially random.

5 Experiment 1

We began with a transparency display consisting of a square-wave grating with full contrast in the surround, and low contrast in the center (see figure 10a). This generates the percept of a mid-gray transparent surface overlying the full-contrast grating. We then blurred the grating in the central region by convolving the square wave with Gaussians of increasing values of σ. Since these convolutions compressed the luminance range of the grating, we then renormalized the blurred gratings so that they had the same peak and trough (L_{max} and L_{min}) as the original grating. The resulting displays are shown in figures 10b – 10e, and their luminance profiles are shown in figure 11. All displays (with the different degrees of blur) now have the same luminance

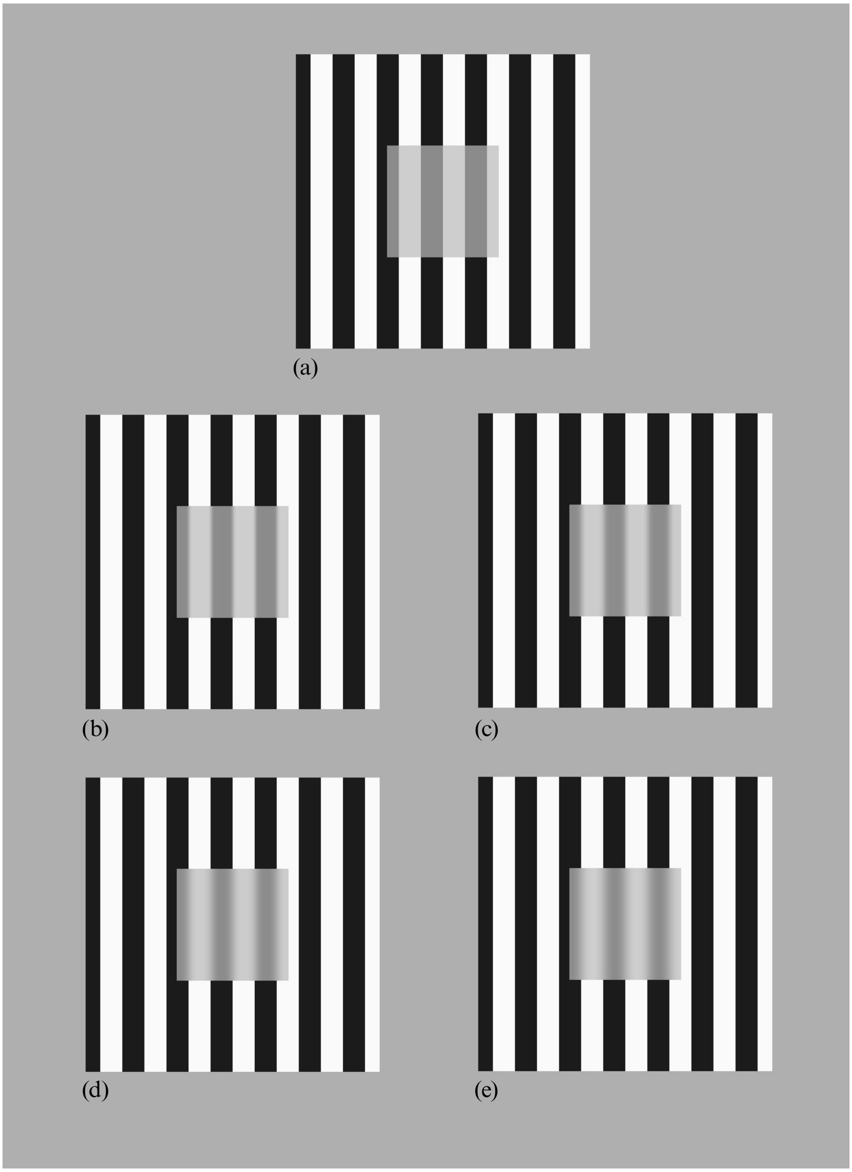


Figure 10. The displays used in experiment 1 to study how the visual system assigns transmittance to translucent layers that scatter light, thereby blurring the contours on underlying surfaces. The central regions in all displays have the same amplitude and Michelson contrast.

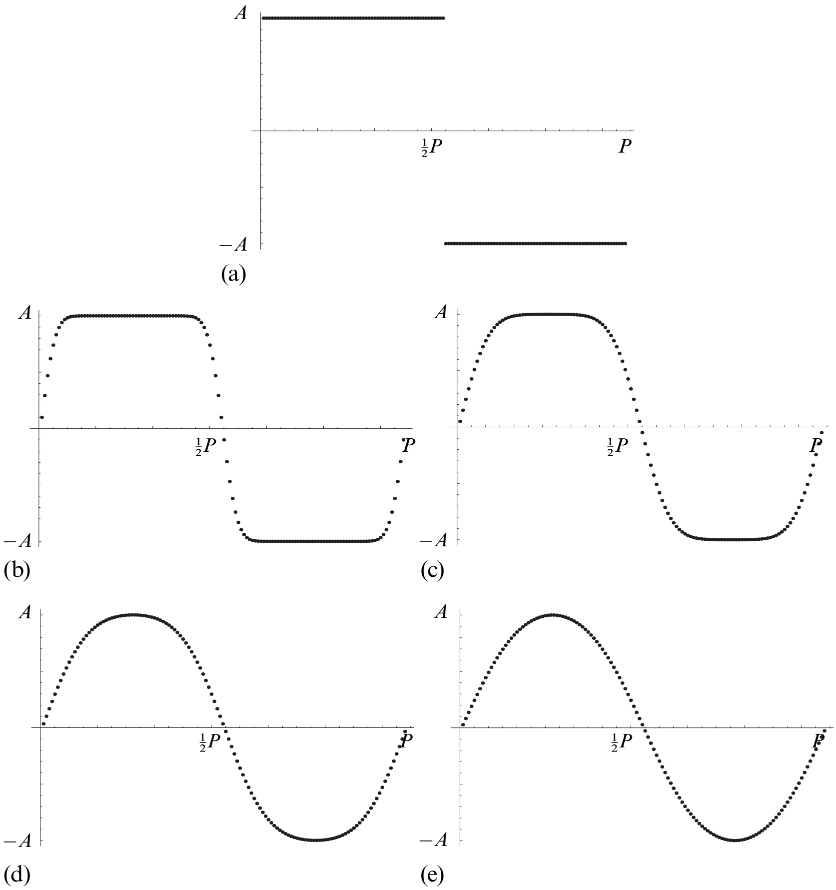


Figure 11. The luminance profiles of the gratings that define the regions of transparency for the displays shown in figure 10. These were created by convolving the square wave—shown in (a)—with Gaussians of different values of σ, and then renormalizing their amplitudes.

range, and the same Michelson contrast, within the central region. These displays thus allow us to study the effects of blur on the perceived opacity of a translucent layer.

5.1 *Methods*

5.1.1 *Observers.* Three observers with normal or corrected-to-normal vision participated in the experiment. One observer was naïve to the purposes of the experiment (RF), and the other two were authors (MS and BA).

5.1.2 *Stimuli and apparatus.* Each test display consisted of a large square region containing a vertically oriented square-wave grating (see figure 12). The side of the large square subtended 4.4 deg and it was placed on a mid-gray background (luminance = 44.91 cd m^{-2}). The spatial frequency of the square-wave grating was 1.51 cycles deg^{-1} (period = 0.662 deg), its mean luminance was 44.91 cd m^{-2}, and its luminance range was 84.84 cd m^{-2} (Michelson contrast = 0.945). A smaller square was placed inside the large one (the 'target square'). Its side subtended 1.68 deg. This smaller square had the same mean luminance (44.91 cd m^{-2}) as the surround, but a lower contrast. Three different values of Michelson contrast in the smaller square were tested: 0.236, 0.354, and 0.472. These corresponded to luminance ranges of 21.23, 31.83, and 42.44 cd m^{-2}, respectively. (The blurring procedure was thus applied to three displays with different contrast values in the target square.)

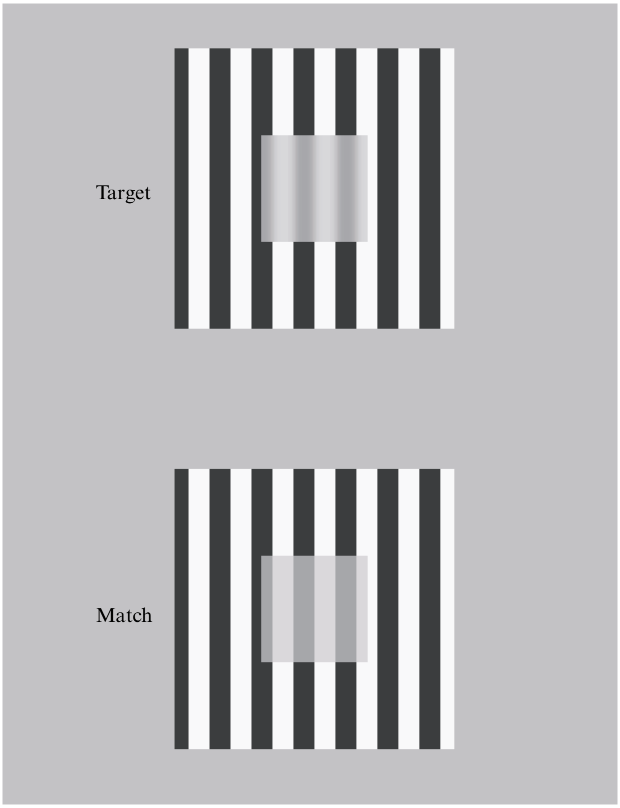


Figure 12. A view of the experimental screen in experiment 1. Observers matched the perceived opacity of the translucent square in the target display by adjusting the luminance range (amplitude) within the transparent square in the matching display.

Five versions of each target square were created by convolving the square wave in the central region with Gaussians with different standard deviations (σs). The five values of σ used were $0P$ (no blurring), $0.25P$, $0.5P$, $0.75P$, and P, where P = period of the square wave. After convolution, the luminance range within each grating was renormalized so as to match the amplitude (and hence Michelson contrast) of the original square wave. The five displays thus created (for the intermediate contrast of 0.354) are shown in figure 10.

A matching display was placed 2.18 deg below the target display. This was similar to the target display (see figure 12), except that the grating within its central region was always a square wave (ie no blurring was added to the matching display). The luminance range within this central region was to be adjusted by the observer.

The displays were presented on a high-resolution (1600 pixels $\times$ 1200 pixels) Radius PressView 17SR monitor, which was calibrated so that luminance values were linearly related to the 8-bit look-up-table values (ranging from 0.58 cd m^{-2} to 90.14 cd m^{-2}). All displays were viewed at a distance of ~100 cm.

5.1.3 *Procedure.* Each observer ran three blocks of trials, one block for each of the three values of contrast within the target square. On each trial, the degree of blur added to the square-wave grating within the target region was randomly set to one of the five preset values. The observer's task was to adjust the luminance range (amplitude) within the small square in the matching display, so as to match the perceived transmittance (or opacity) of the target square (see figure 12). The luminance range increased and decreased symmetrically about the preset value of mean luminance. In each block, observers performed six adjustments for each of the five levels of blur. The first adjustment for each level of blur was taken as practice, resulting in five experimental adjustments for each level of blur.

5.2 *Results and discussion*

The data for the three observers are shown in figure 13. Each curve represents an observer's settings of luminance range within the small square in the matching display, to match the perceived transmittance (or opacity) of a target square with fixed Michelson contrast. The different curves within each observer's data represent matches to targets of different contrasts.

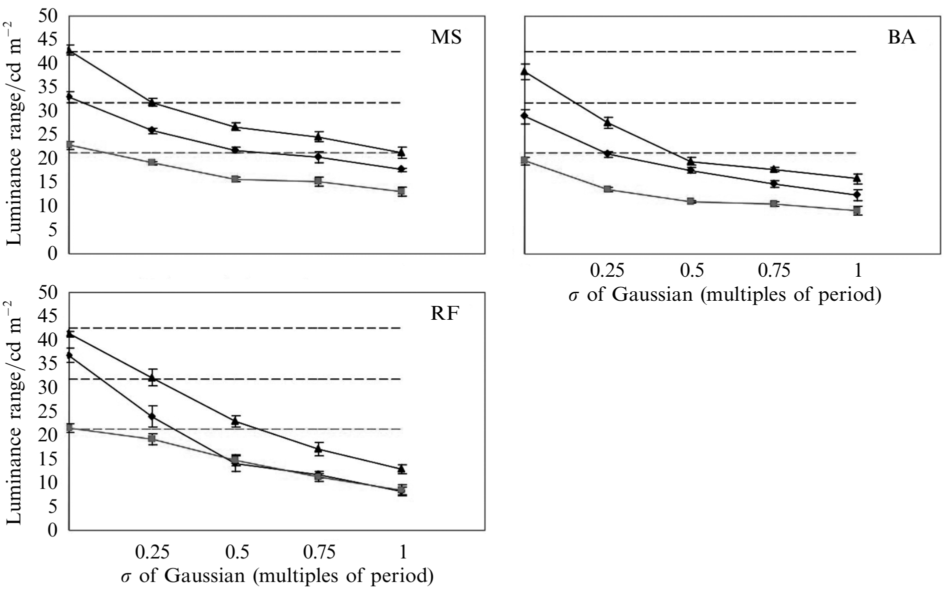


Figure 13. Transmittance-matching data for the three observers in experiment 1. The different curves correspond to matches to different target squares (ie with different contrasts). The results demonstrate that increasing the degree of blur in the region of transparency decreases perceived transmittance, even if Michelson contrast is kept constant.

As can be seen clearly and consistently across observers, increasing the amount of blur in the region of transparency leads to a lowering in the perceived transmittance of a transparent layer. The average factor by which perceived transmittance was lowered [(mean match for no blur)/(mean match for blur with $\sigma = P$)] was 1.87 for observer MS, 2.3 for observer BA, and 3.41 for observer RF. (These correspond to a 46.5% decrease for MS, a 56.5% decrease for BA, and a 70.6% decrease for RF.) This lowering in perceived transmittance occurred even though the luminance range and Michelson contrast were constant across the different degrees of blur.

These data show that for *translucent* layers that contain a significant scattering component, perceived transmittance is not determined simply by the Michelson contrast in the region of translucency. Our previous results concerning the assignment of perceived transmittance to transparent layers thus do not carry over directly to the perception of translucency. Observers perceptually confuse the scattering component of the translucent layer with its absorptive (or contrast-reducing) component. As a result, increases in the degree of blur in the region of transparency are interpreted as increases in the opacity of the transparent layer, even if the Michelson contrast is kept unchanged.

A natural question is whether this result has to do with translucency per se, or whether it is simply a contrast effect. In other words, does the decrease in perceived transmittance follow simply from a concomitant decrease in apparent contrast? For example, a sine wave appears to have somewhat lower contrast than a corresponding square wave with the same peak and trough (eg Ginsburg et al 1980; Georgeson 1991; Georgeson and Shackleton 1994). This is consistent with evidence both from contrast-threshold experiments (Campbell and Robson 1968) and from contrast-matching experiments (Ginsburg et al 1980), and indicates that the apparent contrast of a grating is biased toward its fundamental amplitude (ie the amplitude of its fundamental frequency). Since the blurred versions of the square wave in figures 10b – 10e all have lower fundamental amplitudes than the corresponding square wave in figure 10a, they would indeed be perceived as having lower contrast. Thus the possibility remains that perceived relative contrast consistently determines perceived opacity irrespective of whether or not blur is present, and the results of experiment 1 simply reflect the inadequacy of Michelson contrast in capturing apparent contrast in these displays.

Note, however, that since the fundamental amplitude of a square wave is $4/\pi$ times that of a corresponding sine wave, a contrast measure based on fundamental amplitude would predict an effect no larger than $4/\pi$, or ~ 1.27, in our displays (ie a decrease in perceived transmittance of no more than 21%). The mean magnitude of the effect obtained in experiment 1, however, was 2.53—or a 60.5% overall decrease in perceived transmittance. Thus, these results cannot be attributed simply to the lowering in the fundamental amplitude of the square-wave grating that results from blurring. Similarly, the results cannot be attributed to a decrease in root-mean-square (RMS) contrast (Moulden et al 1990) since the standard deviation of luminance values in a sine-wave grating is only 29.2% lower than that of a square wave.

To study directly the extent to which the results of experiment 1 might be explained by a lowering in apparent contrast, we conducted a control experiment in which observers matched the apparent contrast of the target regions used in experiment 1—except that these were now placed in contexts that did not generate percepts of transparency.

6 Experiment 2

We embedded the target regions used in experiment 1 in zero-contrast surrounds, so that the resulting displays no longer give rise to the percept of transparency (see figure 14). In these displays, there is no percept of a transparent layer, and hence no meaningful notion of perceived transmittance. This modification was applied both to the target displays and to the matching displays so there would be no differential effects of induced contrast from different surrounds—see for example Chubb et al (1989). We then performed a contrast-matching task using these modified displays.

6.1 *Methods*

6.1.1 *Observers.* The same three observers participated as in experiment 1.

6.1.2 *Stimuli and apparatus.* The stimuli were identical to those used in experiment 1, with one exception: the surround of each target and matching display was homogeneous gray, with the same mean luminance as the central region (44.91 cd m^{-2}; see figure 15).

The same three values of Michelson contrast were tested as in experiment 1 (0.236, 0.354, and 0.472) and, for each of these, the same five levels of blur were applied—while keeping Michelson contrast fixed. As in experiment 1, no blur was added to the matching display.

6.1.3 *Procedure.* Each observer ran three blocks of trials, one block for each of the three values of contrast within the target square. On each trial, the degree of blur was randomly set to one of the five preset values. The observers' task was to adjust the

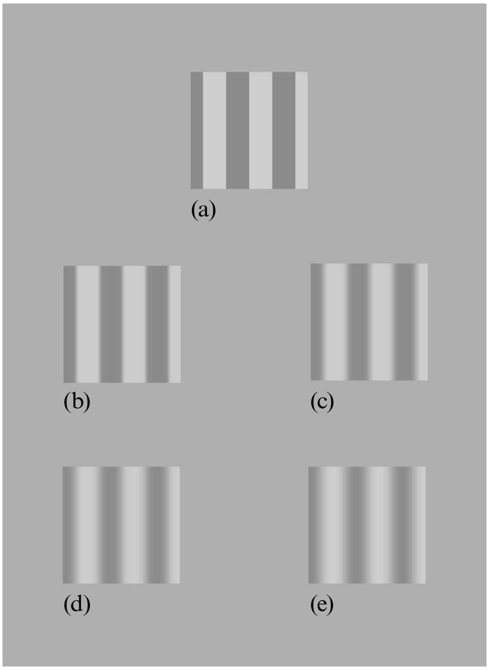


Figure 14. The displays used in the contrast control experiment. These target squares are identical to the central regions in figure 10, except that they are placed in contexts that do give rise to percepts of transparency. The goal was to test how the manipulation of blur in experiment 1 affects apparent contrast, in the absence of perceived transparency.

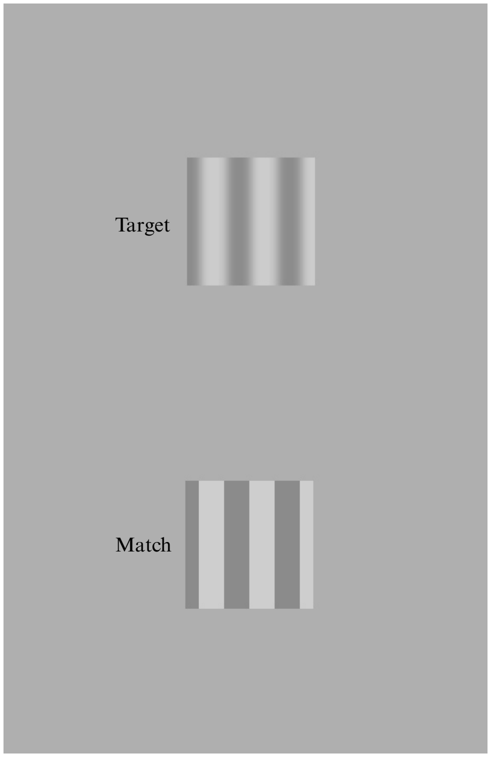


Figure 15. A view of the experimental screen in experiment 2. Observers matched the apparent contrast of the blurred square wave in the target display, by adjusting the luminance range of the square wave in the matching display.

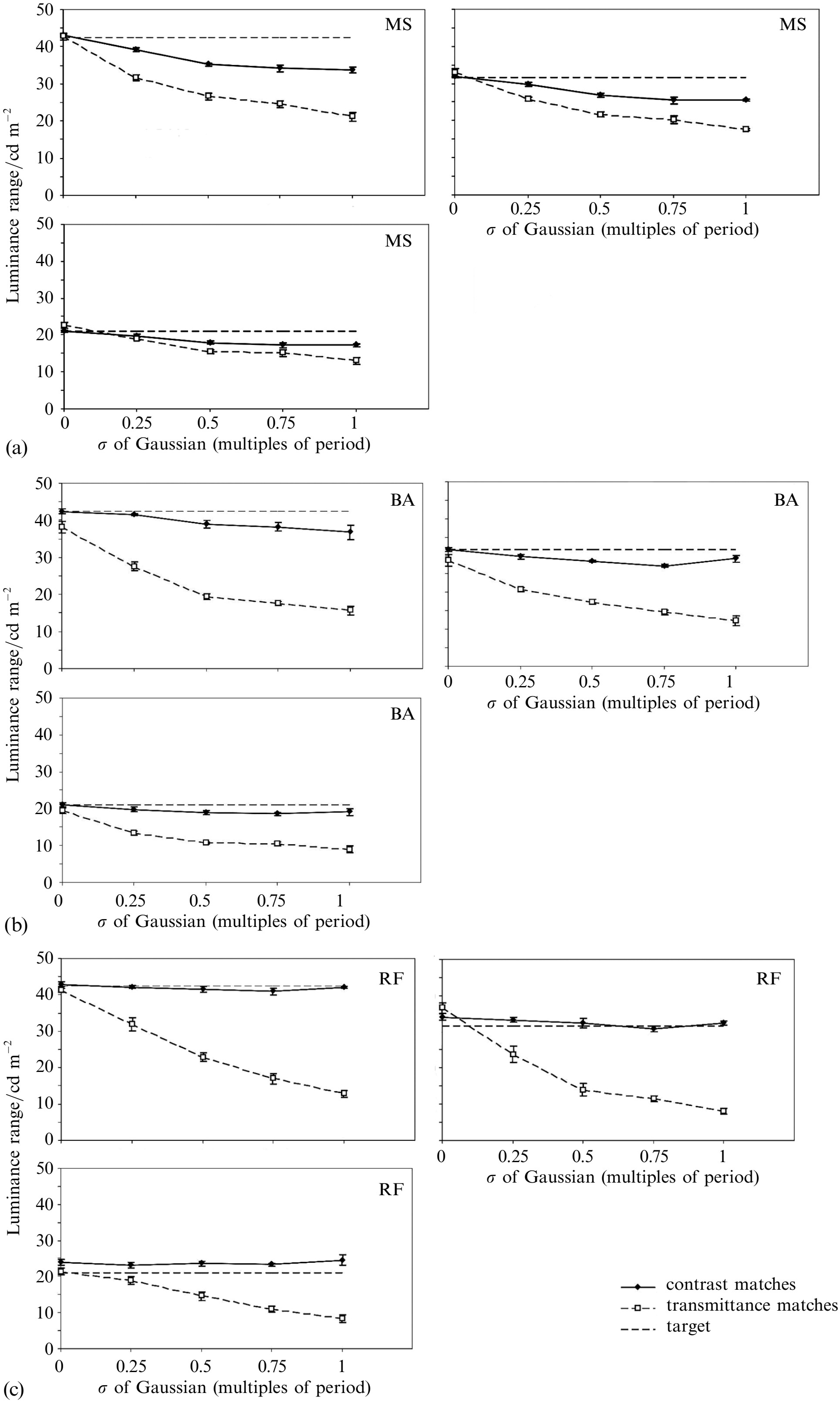
luminance range (amplitude) within the matching display, so as to match the apparent contrast of the target (see figure 15).

6.2 *Results and discussion*

The data for the three observers are shown in figure 16. Each curve represents an observer's settings of luminance range within the matching display, to match the apparent contrast of a target display with fixed Michelson contrast.

The data show that increasing the degree of blur (while preserving Michelson contrast) leads to a lowering in apparent contrast. However, the magnitude of this lowering is small relative to the lowering in perceived transmittance observed in experiment 1. The average factor by which apparent contrast was lowered [(mean match for no blur)/(mean match for blur with $\sigma = P$)] is 1.25 for observer MS, 1.11 for observer BA, and 1.02 for observer RF. (These correspond to a 20% decrease for MS, a 9.9% decrease for BA, and a 1.96% decrease for RF.) Note that these effects are no greater than the magnitude of lowering predicted by a contrast measure based on the fundamental amplitude (namely, $4/\pi = 1.273$, or a decrease of 21%). Indeed, the largest decrease obtained in any condition is 1.28 (observer MS, for target contrast of 0.472).

Figure 16 (opposite). Contrast-matching data for the three observers in experiment 2. Also shown (in dashed lines) are the corresponding transmittance-matching data from experiment 1. The three graphs for each subject represent the results for targets with different contrasts. The results demonstrate that, although the addition of blur does lead to a lowering in apparent contrast, the magnitude of this decrease is relatively small—and hence not sufficient to explain the decrease in perceived transmittance observed in experiment 1.


Luminance range/cd m^{-2}
σ of Gaussian (multiples of period)
MS
BA
RF
0
0.25
0.5
0.75
1
0
10
20
30
40
50
(a)
(b)
(c)
contrast matches
transmittance matches
target

Therefore, although our manipulation of blur does lead to a lowering in apparent contrast, the magnitude of this decrease is not sufficient to explain the decrease in perceived transmittance observed in experiment 1. (Recall that the mean effect sizes in experiment 1 were 1.87, 2.3, and 3.41, for observers MS, BA, and RF, respectively.) Indeed, the proportion of decrease in perceived transmittance attributable to a lowering in apparent contrast is 0.668 for observer MS, 0.482 for observer BA, and 0.298 for observer RF. In matching perceived opacity, observers thus genuinely confuse the scattering component of a translucent surface with its absorptive (or contrast-reducing) component. This indicates that the visual system takes the presence of blur as an additional cue (ie in addition to contrast reduction) when assigning opacity to translucent surfaces—the higher the blur, the lower is the perceived transmittance.

7 Conclusions

Perceptual transparency is a unique visual problem that requires the construction of two distinct surfaces (or material layers) along the same line of sight—an underlying opaque surface, and a partially transmissive surface through which the opaque surface is seen. One aspect of the problem of transparency is studying how the visual system 'discounts' the contributions of interposed partially transmissive surfaces or media, so that the intrinsic properties of underlying surfaces may be recovered. According to this approach, the problem of transparency is another instance of the more general problem of lightness constancy (Adelson 2000) or color constancy (D'Zmura et al 2000). However, another equally important aspect of perceptual transparency is assigning surface properties to the transparent layer itself. When we encounter transparency in the world, we are aware not only of the surface properties of underlying surfaces, but also of those of the interposed transparent layer—in particular, its transmittance and its lightness. Furthermore, as the transparent layer becomes less transmissive, we are aware more of the transparent layer, rather than the underlying layer (compare the display in figure 2c with that in figure 2a).

Most work on perceptual transparency—including very recent work (see section 3)—has supported the view that perceptual transparency is consistent with Metelli's episcotister model (but see Beck et al 1984). However, we have recently shown that the perception of surface transmittance and lightness deviates systematically from the predictions of Metelli's equations. In particular, whereas Metelli's solution for α predicts that perceived transmittance should be given by relative luminance differences in the region of transparency, we demonstrated that it is determined instead by relative Michelson contrast (Singh and Anderson 2002). The use of Michelson contrast leads observers to systematically overestimate the transmittance of darkening transparent layers (that decrease the mean luminance in the image region containing transparency, relative to adjoining regions), and to systematically underestimate the transmittance of lightening transparent layers (that increase mean luminance in the region of transparency).

In the current paper, we studied the contributions of another critical image variable in determining perceived opacity, namely the image blur that results from the light-scattering properties of translucent layers. Our results showed that Michelson contrast, by itself, is not sufficient to predict perceived transmittance for translucent layers: adding blur to the region of transparency (relative to adjoining regions) decreases perceived transmittance, even if Michelson contrast is preserved (experiment 1). Moreover, this result is not accounted for by the small decrease in apparent contrast that results from such blurring (experiment 2), nor by the decrease in the fundamental amplitude or RMS contrast of the blurred square wave. Thus, the visual system treats the presence of blur as an additional image cue when assigning transmittance (ie in addition to contrast reduction). In experiment 1, a Gaussian blur with σ equal to the period of the underlying square wave led to an average of 60% decrease in perceived transmittance. However, the magnitude of decrease was somewhat variable across observers. This variability stands in sharp contrast to the high degree of consistency we found across observers in our previous transmittance-matching experiment (experiment 1 in Singh and Anderson 2002). In the absence of image blur, Michelson contrast provided an excellent quantitative predictor of observers' transmittance matches. This suggests that the assignment of surface opacity is less robust for partially transmissive surfaces that contain a significant scattering component. This is perhaps not surprising given that the degree of image blur and contrast in the region of translucency depend on a number of environmental contingencies that have nothing to do with the intrinsic surface properties of the translucent layer. For example, increasing the distance between a translucent layer and an underlying surface increases the degree of image blur, and decreases Michelson contrast (see figure 17). This, in turn, makes the translucent layer appear less transmissive, even though its intrinsic surface properties have not changed. Similarly, changing the period of a texture grating on an underlying surface also makes the translucent layer appear less transmissive (figure 18).[3] To the extent that the visual system is unable to 'factor out' the contributions of these variables, image blur is likely to serve as a less reliable cue to surface opacity.

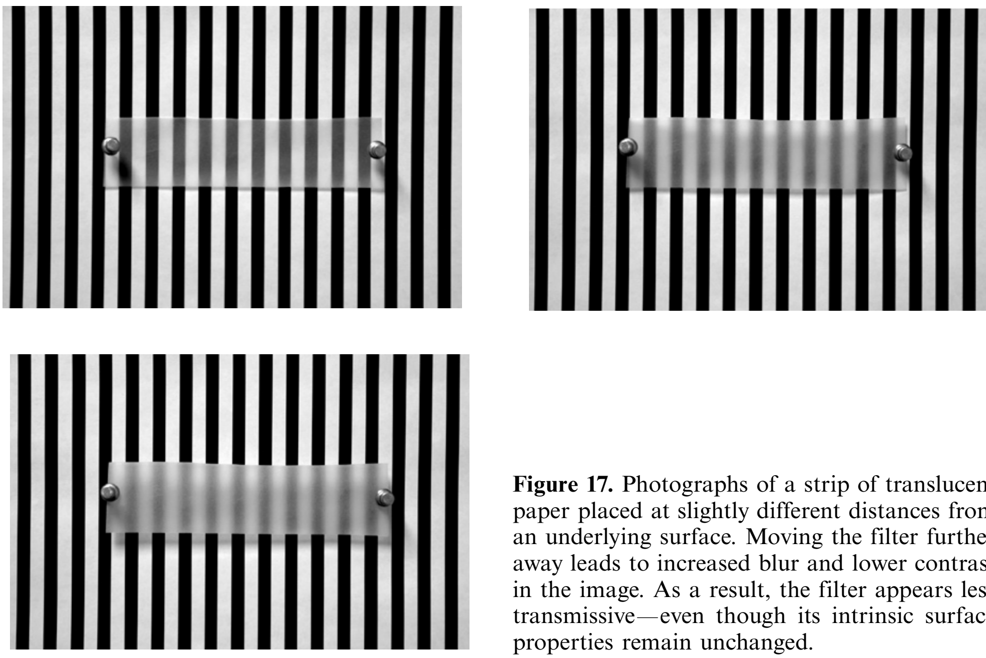
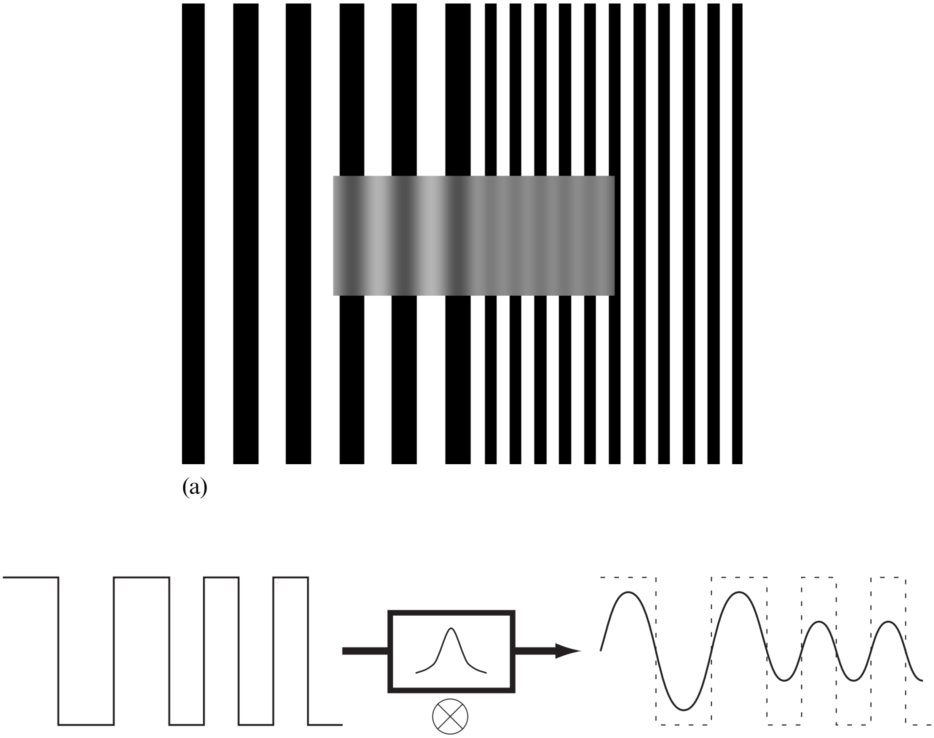


Figure 17. Photographs of a strip of translucent paper placed at slightly different distances from an underlying surface. Moving the filter further away leads to increased blur and lower contrast in the image. As a result, the filter appears less transmissive—even though its intrinsic surface properties remain unchanged.

Our result concerning the combined role of image contrast and image blur in determining the perceived transmittance of partially transmissive surfaces parallels recent work in the perception of surface reflectance. In that context, contrast and blur have been found to be the primary determinants of apparent gloss, ie how shiny a surface appears (Pellacini et al 2000; Fleming et al 2001). The parallels between the apparent gloss of an opaque surface and the perceived opacity of a partially transmissive surface make sense given that both contexts involve seeing one surface *through* another. In both cases, information from two surfaces collapses onto a single pattern

[3] If the scattering effect of a translucent layer is modeled as a convolution with a fixed point-spread function, this convolution will clearly lead to a greater reduction in contrast for higher-frequency gratings (see figure 18b).



(a)

(b)

Figure 18. (a) Demonstrating the effect of the period of the underlying grating on the perceived opacity of a translucent layer. (b) Convolution with a fixed point-spread function leads to a greater decrease in contrast for the higher-frequency grating.

of light intensities and, in both cases, the visual system must decompose this pattern of intensities to extract two surfaces along each line of sight. (To further appreciate this analogy, note that seeing an object reflected in a perfectly glossy surface—eg a polished mirror—is optically identical to seeing it through a perfectly transmissive surface—eg a clear glass pane.)

In the current paper, we considered how the presence of image blur modulates the perceived opacity of a partially transmissive surface given that the percept of two distinct surfaces—one seen through the other—has been initiated. However, another basic question in perceptual transparency is: when does the visual system initiate a decomposition into two distinct surfaces in the first place? In the context of transparency that does not involve image blur, researchers have consistently argued that (some measure of) image 'contrast' must be lowered in the region of putative transparency. The relevant notion of 'contrast' has been variously defined in terms of reflectance or luminance differences (Metelli 1974a; Gerbino et al 1991), lightness differences (Beck et al 1984), and Michelson contrast (Singh and Anderson 2002). A precise formulation of this is that the visual system *anchors* the highest-contrast regions in an image to full transmittance (ie it treats them as being seen in plain view), and it decomposes the lower-contrast regions into multiple layers (Anderson 1999). Although this rule works well in the context of partially transmissive surfaces and materials that do not scatter light (eg figure 19a), the display in figure 19c demonstrates that *translucency* introduces an additional image dimension that is not captured simply in terms of 'lower contrast'. In particular, although any of the previously considered measures of contrast would unambiguously assign lower contrast to the central region in figure 19c, this region

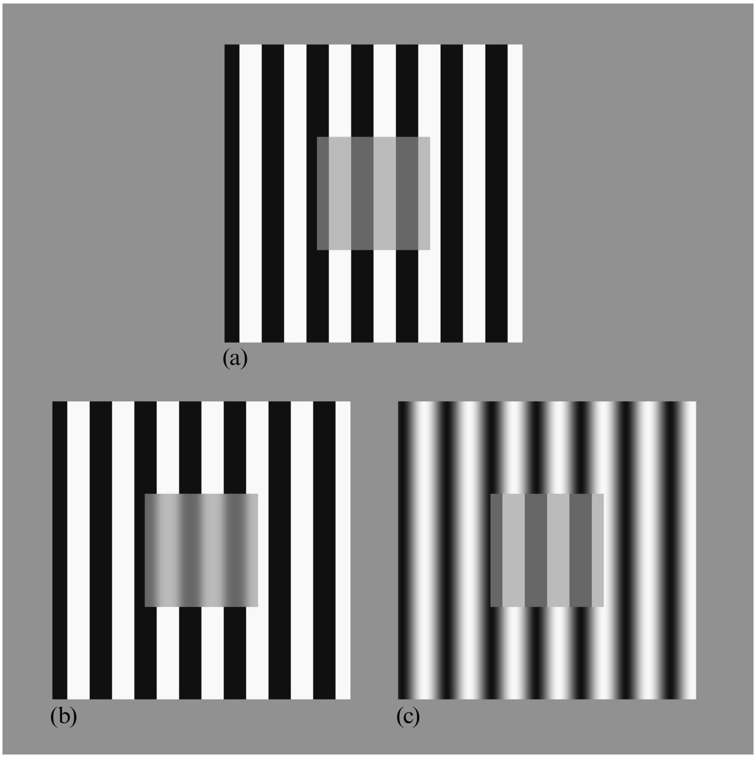


Figure 19. Demonstrating the role of image blur in initiating a decomposition into multiple surfaces—one seen *through* another. (a) In the absence of blur, the lower-contrast center decomposes into two distinct surfaces. (b) If blur is present on the low-contrast center, it still decomposes into two separate layers. (c) However, if blur is present on the high-contrast surround, then this decomposition does not occur (neither the center nor the surround appears to contain an overlying layer). Thus percepts of multiple layers are obtained only if the cues of contrast reduction and image blur are consistent with each other.

does not decompose perceptually into two distinct layers (compare with figures 19a and 19b). This indicates that image blur is an additional image cue used by the visual system even to *initiate* the decomposition of an image region into distinct surfaces. Moreover, this cue must be consistent with the contrast-reduction cue (ie the image blur must be present in the lower-contrast region), otherwise percepts of one surface seen through another are not initiated.

Acknowledgments. We thank Ted Adelson for many discussions on the topic of translucency; and Roland Fleming, Alan Gilchrist, and an anonymous reviewer for helpful critiques on previous versions of the manuscript.

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