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Transparency: relation to depth, subjective contours, luminance, and neon color spreading

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Abstract. The perception of transparency is highly dependent on luminance and perceived depth. An image region is seen as transparent if it is of intermediate luminance relative to adjacent image regions, and if it is perceived in front of another region and has a boundary which provides information that an object is visible through this region. Yet, transparency is not just the passive end-product of these required conditions. If perceived transparency is triggered, a number of seemingly more elemental perceptual primitives such as color, contour, and depth can be radically altered. Thus, with the perception of transparency, neon color spreading becomes apparent, depth changes, stereoscopic depth capture can be eliminated, and otherwise robust subjective contours can be abolished. In addition, we show that transparency is not coupled strongly to real-world chromatic constraints since combinations of luminance and color which would be unlikely to arise in real-world scenes still give rise to the perception of transparency.

Rather than seeing transparency as a perceptual end-point, determined by seemingly more primitive processes, we interpret perceived transparency as much a 'cause', as an 'effect'. We speculate that the anatomical substrate for such mutual interaction may lie in cortical feed-forward connections which maintain modular segregation and cortical feedback connections which do not.

1 Correlation between neon color spreading, transparency, subjective contour, and depth

Various visual features of an object such as its shape (contour), depth, luminance, and color are perceived as separable. But, at the same time, these features are linked and perceived as different aspects of the same object. It is presumably for this reason that the relationship between these various aspects of visual processing is now becoming an important issue for current research.

For example, consider properties such as depth, transparency, subjective contour, and neon color spreading. Although these phenomena have been often treated as separate topics, they are highly correlated in some cases. As an illustration of this point, consider the 'Ehrenstein' configuration in figure 1a derived from earlier demonstrations of Ehrenstein (1941), van Tuijl (1975), Redies and Spillman (1981), and Redies et al (1984).

Even though the gray center of the cross (seen in figure 1a) is physically restricted, the brightness (color) of the inner cross appears to spread, forming a pale disk-like array which encroaches on the black background. Besides this brightness (color) spread effect, three additional features are notable. First, there is a connection to subjective contours because the color seems to be 'contained' within a sharp subjective contour which defines a disk. Second, there is often a clear perception of transparency. One has the impression of viewing a cross through a transparent filter.

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The third feature is the linkage of transparency and subjective contours to the perception of depth, since the transparent disk bounded by the subjective contour is generally seen in front of the cross.

Redies and Spillman (1981) and Redies et al (1984) characterized the conditions under which such spreading is apparent. Among others, collinearity between the inner and outer limbs of the cross was of major importance since small misalignments led to a reduction of the effect (see figure 1b). The length of the outer arm of the cross was unimportant: shortening it almost to the point of invisibility did little to reduce the effect. However, removing the outer arms abolished the color spreading. Redies et al (1984) further noted that just a small gap in the cross (where the inner limb meets the outer limb) is sufficient to reduce the spreading (see figure 1c). Interestingly, the perceptions of subjective contours, transparency, and depth are also weakened in these cases.

The strong association among these perceptual properties is intriguing because it seems to 'make sense', in terms of the ecological optics of transparency. Note that the manipulations which reduced neon color spreading in the studies of Redies and collaborators (the breakage of collinearity, separation of collinear line segments) are ones that also reduce the possibility that the scene can be interpreted as including a transparent surface. One cannot easily assume, for example, that a transparent gray disk covers a white cross (in figure 1) if the inner limbs of the cross are not collinear with the outer limbs (figure 1b) or if there is a break between the inner and outer limbs (figure 1c). It is as if the visual system is providing a coherent or 'intelligent' 3-D interpretation of the image (however, see section 5 for further discussion).

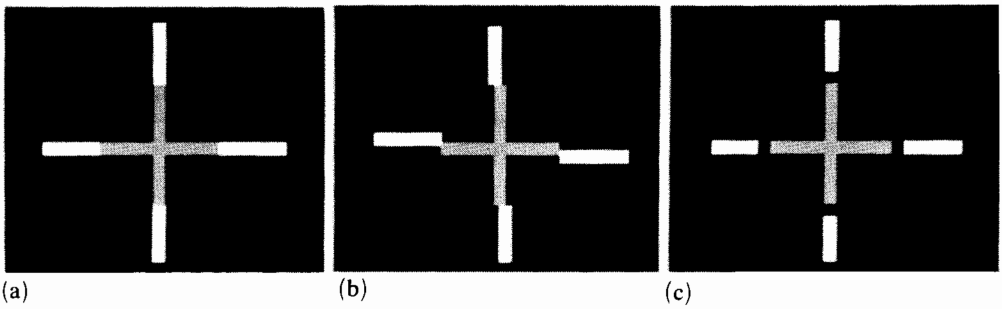

Figure 1. Ehrenstein configuration. (a) Note that the color of the inner gray cross spreads so that it looks like a transparent disk occluding a larger cross. When the arms of the outer cross are not collinear with the inner limbs (b) or when there is a gap between them (c), color spreading is reduced. [Modified from demonstration of Redies and Spillman (1981, 1984).]

2 Critical role of depth

Because of this possibly close relationship between 3-D scene interpretation and the perception of transparency, our initial research strategy was to accentuate depth. Binocular disparity seemed to be an ideal choice since it allows one to alter perceived depth in a reliable and metrical fashion, without introducing obvious changes in the monocular configurations. So we began the investigation by examining a variety of spatial configurations which have been associated with neon color spreading and manipulated the disparity between the various figural elements.

To save space and yet to see all configurations in normal and reversed disparity conditions, we reproduce stereograms having three rather than the usual two half images. The center image can be used twice, to form a stereogram either with the left and center image or, its reversed disparity case, with the center and right image.

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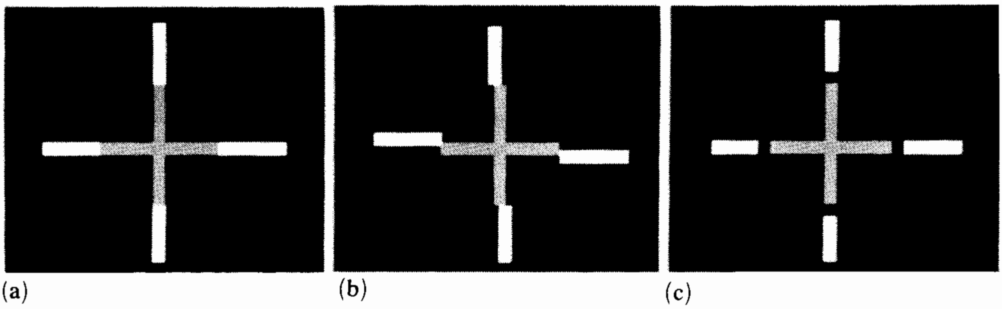

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In this way, observers who cross or uncross their eyes can observe two cases with opposite signs of disparity.

First we should mention that the simple reversal of disparity has already yielded some very striking results in relation to subjective contours. Varying disparity in the conventional Kanizsa square, for example, can be decisive in subjective contour formation (Bloomfield 1973; Lawson et al 1974; Gregory and Harris 1974; Ramachandran and Cavanagh 1985). The stereograms in figure 2 demonstrate this clearly. In the crossed disparity case, the usual subjective contours are seen as greatly enhanced and the Kanizsa square is seen in front of the disks (figure 3a). This is no surprise because disparity accentuates the depth relations that are implied by the existence of the subjective contours. When the disparity is reversed, however, the vertical and horizontal contours of the subjective square are abolished or greatly attenuated. Instead, the configuration may be seen as four circular windows through which one sees the four corners of an occluded square. Consistent with this interpretation, a new set of subjective contours is apparent, curved arcs which complete the perception of the four circular windows (figure 3b). Absent are the usual contours that complete the 'square' in this well-known Kanizsa configuration. Figure 3 provides a pictorial representation of these two distinct sets of subjective contours. This demonstration indicates that depth relations alone, as defined by binocular disparity, can have a major role in the formation and suppression of subjective contours.

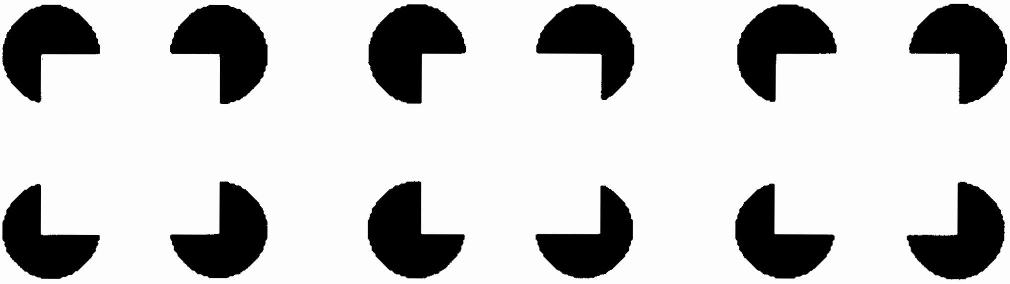


Figure 2. Subjective contours and stereopsis. In this and all other stereograms, the observer can fuse either the left and center images, or the center and right images. If the left pair is fused by crossing the eyes (hereafter called the crossed or correct case), one sees a Kanizsa square in front of occluded disks. If one fuses the right pair by crossing the eyes (hereafter called the uncrossed case), one sees portholes through which the tabs of squares are seen (see text). These two perceived configurations will be reversed if one fuses the pairs with uncrossed eyes. [Adapted from Gregory and Harris (1974).].

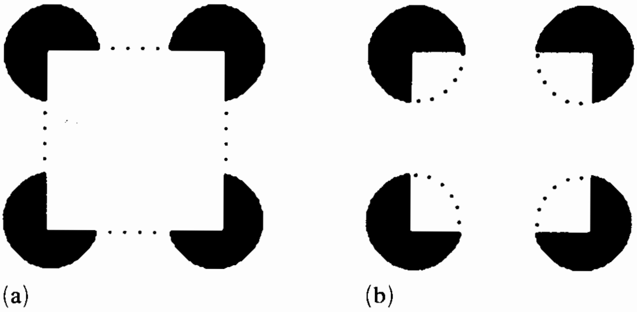


Figure 3. Pictorial description of the mutually exclusive sets of subjective contours which are seen in figure 2: (a) vertical and horizontal contours; (b) curved contours completing the circular 'windows'.

Our question is whether an equally potent role of disparity can also be seen for the perception of transparency and possibly for color spreading as well. In our first demonstration of this effect, we modified an already existing pattern (Redies and Spillman 1981) manipulating its apparent depth by varying the disparity of the horizontal inner limb of the cross. This simple manipulation had a dramatic effect on the perception of the inner portion of the cross (see figure 4 and plate 1a). Furthermore, the 'quality' of the color was very different in the two cases, corresponding to the 'surface' versus 'film' color distinction made by Katz (1935). In the uncrossed

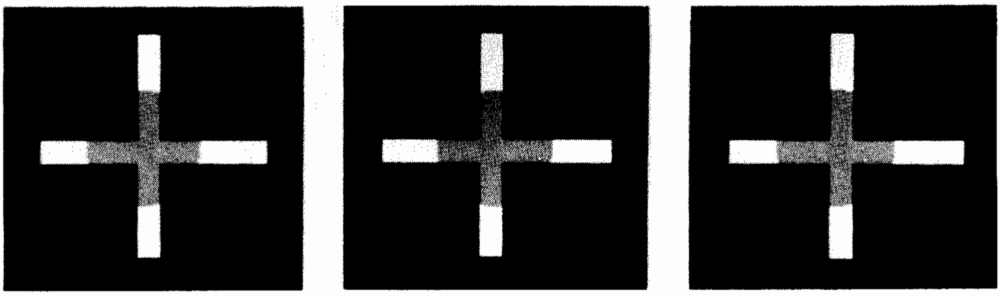
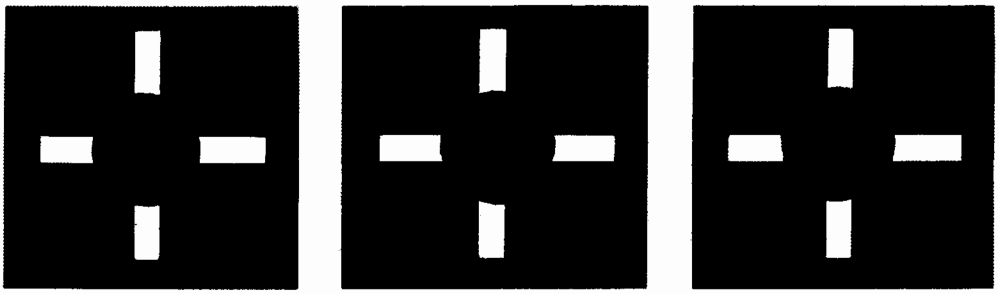


Figure 4. The same configuration as that seen in figure 1a except that the horizontal limbs of the inner cross are in crossed or uncrossed disparity. Note the perception of transparency and color spreading in the crossed case and their absence in the uncrossed case. To see the crossed case, observers who cross their eyes should view the left and center half-images. Similarly, to see the uncrossed case, such observers should fuse the center and right half-images. The opposite is the case if the observer diverges to obtain fusion. Note that this convention holds for all subsequently presented stereograms and for those seen in plate 1.



(a)

(b)

Plate 1. (a) Ehrenstein stereo configuration (seen also in figure 4) except that the central cross is colored red.
(b) Ehrenstein illusion with color arrangement that is not consistent with a real-world interpretation of a colored filter in front, yet inner red cross still appears as a transparent disk occluding a larger green cross.

disparity case, the inner cross is seen as an opaque surface behind a cruciform aperture. In the crossed disparity case, it appears as a transparent film, covering part of the white cross.

In addition to this large difference in surface quality, the spreading of the color into the homogenous black background is very different in the two situations. When the inner cross is seen as behind and opaque, there is very little color spreading into the dark region. On the other hand, if one views the reversed stereogram, the middle region is seen as transparent and there is obvious color spreading onto the black region enclosed by a subjective contour that completes a transparent 'disk'. It should be noted that this spreading is even more enhanced than the original monocular or zero-disparity case (compare the spreading seen in the stereogram with figure 1; also see the quantitative results in the next section).

3 Experiment: ratings of color spreading by naive observers

Qualitative observations in experienced subjects is an appropriate first step to study these phenomena, particularly where we need to make a large number of very different comparisons using a number of spatial configurations. Yet it is also important to quantify at least some of these phenomenological findings in order to establish the fact that, in principle, they can be backed up by more objective and quantitative techniques with naive subjects. To accomplish this goal, we selected four observers with normal stereopsis who had no information as to the purpose or aims of the experiment [one of the authors (SS) also participated as an additional, non-naive subject].

Our approach was to systematically manipulate the disparity of the horizontal limb of the inner cross. Observers viewed a CRT and fused the two images by means of a prism haploscope. The disparity of the test target varied from -18 to $+18$ min visual angle of disparity in five steps with the zero disparity case serving as the standard. Two sets of experiments were run with the five observers. In one of the experimental sets we used an achromatic configuration with a gray inner cross (as seen in figure 4). In the other set we used a chromatic configuration with a red inner cross (as seen in plate 1a). In each, we had the observers rate the degree of color spreading onto the black area, anchoring the scale at 1 for no spreading, at 7 for maximum spreading, and at 4 when it matched the standard. Each person made four judgements for each disparity which were randomly interspersed.

In figure 5 we show the ratings of these observers as a function of disparity (four estimates were averaged for each disparity condition for each subject for the two experiments). The five nearly identical curves indicate that the effect is very robust and reproducible across observers and, most important, they back up the qualitative observations. Furthermore, there is essentially no difference between the two experiments. The spreading of red and gray into the dark background conforms to the same relationship, indicating that we can, for all intents and purposes, consider the spreading of achromatic brightness and that of color as equivalent.

The next several demonstrations are to show that the effect of depth on contour and surface perception is very robust, that it can be seen in a variety of spatial configurations, and that the role of depth is general, not limited to depth signalled by binocular disparity.

The Ehrenstein cross is just one of a potentially infinite number of configurations that can support neon color spreading and in which the color spreading is highly susceptible to the disparity of the array. We now show additional stereo-pairs, this time modifying the standard Kanizsa square by filling in the otherwise empty pacman 'mouths' with a gray or colored sector which completes the disks. Such an approach has been taken before with monocular targets (Varin 1971; Ware 1980; Meyer and

Daughtery 1987). Our contribution is to add stereoscopic disparity such that the vertical contours of the wedge have an either crossed or uncrossed disparity relative to the outer contours of each disk (see figure 6). When the disparity is crossed, transparency and clear spreading of color into the black region is apparent. With reversed disparity, transparency is absent and little or no neon spreading is seen. Again, we see that the perceptions of subjective contours, transparency, and color spreading are highly correlated with each other, and that opposite signs of disparity have drastically different effects on these perceptual surface properties.

The next demonstration deals with the issue of whether the role of depth is more general and whether it can be mediated independently of binocular disparity information. The reader should fuse the Ehrenstein-type patterns seen in figure 7. Here one of the white crosses has the gray area inside whereas the other does not. Rather than seeing the usual rivalry between the two patterns, ie seeing the center part of the cross appear and disappear, one sees something quite unexpected. The gray region alternates between being seen in front and being seen in back.

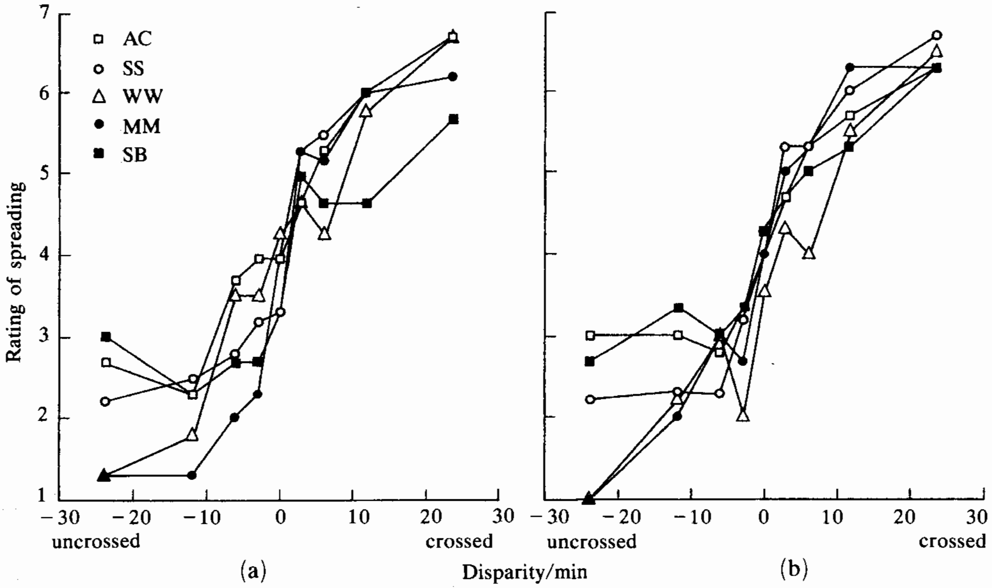


Figure 5. Ratings of perceived spreading of redness (a) or grayness (b) onto the black regions from five naive observers plotted as a function of the binocular disparity of the horizontal limbs of the inner cross.

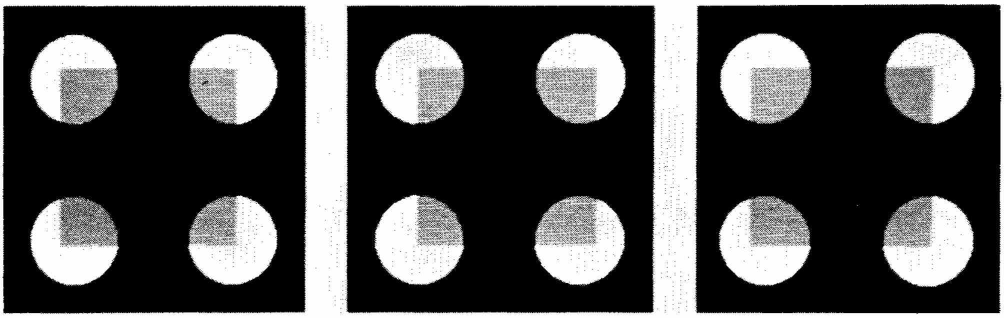


Figure 6. Varin configuration. Kanizsa square with mouths or wedges filled rather than empty. In the crossed configuration, the mouths appear as transparent regions and color spreads clearly. In the uncrossed case, they are seen as behind, and the spreading is abolished or highly attenuated.

Although we have no explanation for the alternation of depth, rather than the usual rivalry, it is most interesting to note that transparency and color spreading are highly correlated with the fluctuations in perceived depth. When the inner gray cross is seen in front, it appears as transparent and the gray color spreads across the black background. Moreover, one can also see a subjective contour enclosing the color within a central disk. On the other hand, when the perception is such that the gray inner region is seen in back, the surface looks opaque, the subjective contour is not apparent, and color spreading is reduced. Furthermore, these effects, which vary with the perceived fluctuations in depth, appear almost as strong and as clear as the dependence of color spreading on disparity (shown in figure 4). This demonstration indicates that depth as mediated by conventional steropsis is unnecessary.

The role of nonstereoscopic depth for neon color spreading was first recognized by Meyer and Daughtery (1987), who relied on Wong and Weisstein's (1984) observation that flickering regions are perceived as being behind nonflickering regions. By manipulating the flicker rate they were able to manipulate depth. Neon color spreading was only seen when the colored region was seen in front. The unique strength of our own demonstration (as shown in figure 7) is that it shows the close relationship between subjective contours, transparency, and neon color spreading. They fluctuate dramatically and in unison. They are dependent on purely perceptual changes in depth, without physical changes in the stimulus. This strongly reinforces our conclusion that they are mutually correlated and linked in an important functional manner.

Results presented so far can be summarized by making two main points: (i) *there is a close linkage among subjective contours, transparency and color spreading*; (ii) *there is a critical and asymmetric effect of depth*.

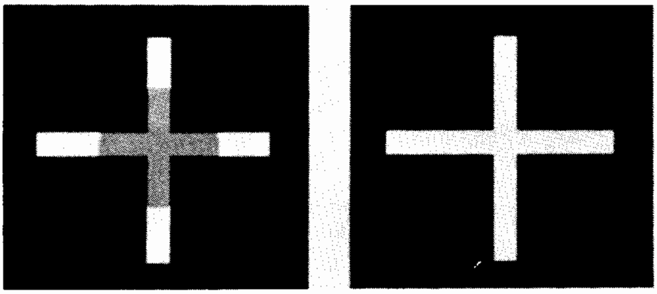


Figure 7. Rivalrous Ehrensten configuration with inner colored cross missing from one half-image. Fusion of these two images leads to a spontaneous fluctuation of depth such that the inner cross is perceived to be either in front or behind the outer cross. When the region of the inner cross is seen in front, it appears as transparent and vigorous color spreading is seen. When this region is seen as behind, transparency and color spreading are reduced.

4 Being in front is not sufficient to trigger transparency

Up until now we have stressed the importance of relative depth as a critical link in the chain. All of the conditions that lead to color spreading and the perception of transparency require that the edge of a transparent surface have crossed disparity. Thus in the series of demonstrations (plate 1a; figures 1a, 4, and 6), transparency is apparent only when an edge of the transparent region is in crossed as opposed to uncrossed disparity.

This, however, is not enough. First, it should be noted that, for the stereograms seen in plate 1a and figures 1a, 4, and 6, at least some boundary or edge of the transparent colored region has the disparity corresponding to a more distant surface.

For example, in the Ehrenstein cross (figure 4 or plate 1a), it should be clear that while the extremities of the horizontal limb of the inner cross have a crossed disparity relative to the outer cross, the vertical edge of the inner cross is collinear with the outer cross. Thus, by necessity, it always has the same disparity as the outer limbs. It therefore cannot be said that the inner cross as a whole has 'crossed' disparity. The horizontal limbs do, but the vertical limbs do not. Similarly, for the Kanizsa (or Varin) configuration in figure 6, the vertical border of the wedge is in crossed disparity to, but the arc enclosing the wedge has the same disparity as, the rest of the disk.

If one thinks of the three-dimensional layout of situations where transparency could occur in the natural world, the otherwise peculiar characteristics of these configurations become more comprehensible. In natural scenes there is usually something that can be seen behind the transparent occluding material. Therefore a key feature for the triggering of perceived transparency might be the existence of image points behind a transparent surface. The next two demonstrations provide further support for this idea.

First we start with a minimalist approach. What is the smallest amount of 'rear' information that can trigger perceived transparency? Would a single point or dot be sufficient? In figure 8, we show two nearly identical stereograms (compare top and bottom). In both cases there is a white rectangle peppered with random dots, all of which are in the same disparity plane as the rectangle. In the middle of each white rectangle there is also a gray rectangle having crossed disparity. The upper and lower stereograms are distinguished only by the disparity of just one binocularly paired dot. This dot is in the middle of the gray region and has a disparity of the gray square in the top stereogram and of the white rectangle in the bottom stereogram. Note the difference in surface appearance of the gray between the upper and lower stereo-

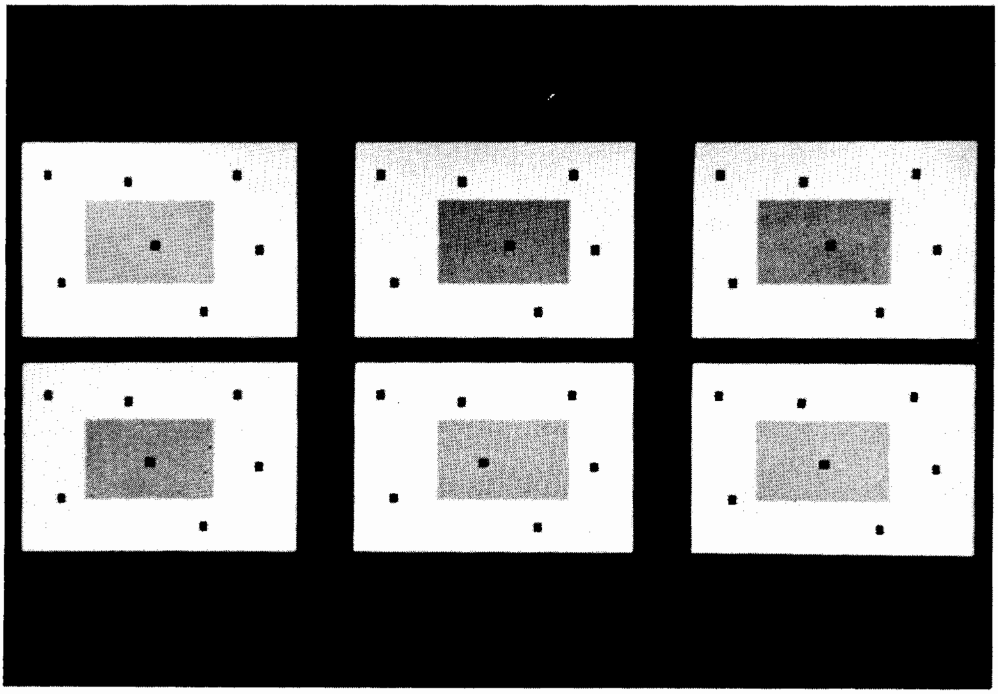


Figure 8. Transparency can be triggered by a single dot. Upper and lower stereograms differ only in the disparity of a single dot which is in the front plane in the top stereogram, and in the rear plane in the bottom stereogram. Transparency is seen only in the lower stereogram.

grams: the gray has the character of an opaque surface in the upper stereogram, whereas it is seen as a transparent surface in the lower stereogram. Thus, a single dot in back is sufficient to trigger perceived transparency.

Our second demonstration can be seen in figure 9. The configuration here is similar to the Varin configuration shown in figure 6. Fusing the image leads to vivid transparency and color spreading in the bottom but not in the top configuration. Why is this the case? In the top stereogram, all of the boundaries of the gray patches have crossed disparity and there is no 'evidence' that the gray is occluding anything behind. Consequently, it appears as an opaque surface bounded by subjective contours and there is no perception of transparency or color spreading. In the bottom stereogram, however, the presence of zero-disparity contours delineates part of the gray region providing evidence that there is a region behind which is occluded. This, in turn, leads to vivid transparency and color spreading.

These two demonstrations show that the simple encoding of a region as 'in front' is not sufficient to elicit the perception of transparency or color spreading: *indicators of an object behind the transparent surface are also of importance*. Also, color spreading cannot be a necessary condition for transparency because transparency occurred without color spreading in figure 8.

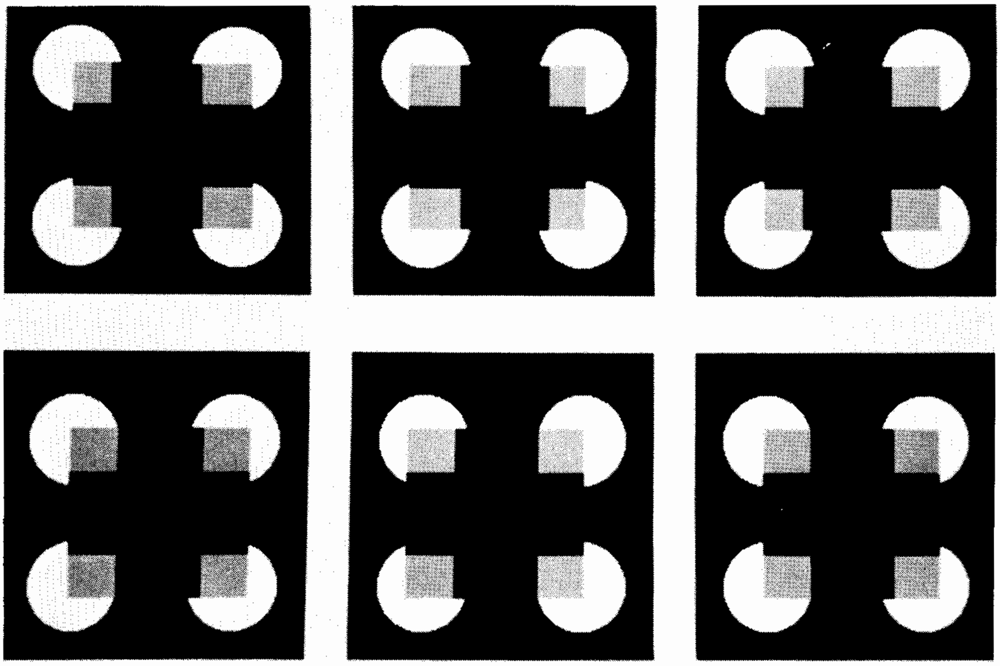


Figure 9. Crossed disparity alone is not sufficient to trigger transparency and neon color spreading. In the upper stereograms (crossed case), the observer sees a Kanizsa square with four gray patches in each corner. Subjective contours are very clear, yet there is no perception of transparency, nor is there any neon color spreading. In this condition, all contours of the gray patches are in crossed disparity. In the lower stereograms, however, the inner borders of the square gray patches are in uncrossed disparity. Here the gray patches look transparent and color spreading is apparent.

5 Transparency mechanisms can determine depth perception

So far we have confined our analysis by considering transparency as a perceptual endpoint, arising from depth, contour, and luminance information. Such an analysis might give the impression that transparency mechanisms are 'higher' than the mechanisms that lead to its expression. Thus transparency might be thought to arise *after* the encoding of depth, luminance, and contour information. In this section we provide demonstrations to indicate that such a view must be an oversimplification because the perception of transparency itself can be decisive in determining perceived depth as well as leading to the formation and destruction of subjective contours themselves.

To see this, examine figure 10, which is identical to figure 6 except that the outer pacmen have been removed, leaving only the inner wedges. Thus, the disparity relations of the various bounding contours of the wedges in figure 10 and figure 6 are identical. Yet a completely different perception of depth is observed. Instead of seeing a nearer transparent square over the region of the wedges, this same 'square' region is now seen as the more distant surface, upon which one sees four partially occluded disks through the opening of a square aperture. Thus, the simple removal of the conditions that lead to the perception of transparency completely changes perceived depth, even though the local disparity signals are the same. In one case, the square region is in front, in the other it is seen in back.

In addition to the straightforward dependence of depth on the triggering of transparency, a more subtle yet rather dramatic difference occurs with the phenomenon of stereo capture. Originally described by Ramachandran and Cavanagh (1985), stereo capture occurs in the presence of a subjective square which appears opaque and forces a repeating motif of background lines to be pulled forward and seen on the closer surface. The stereo capture phenomenon is reproduced in the lower stereogram of figure 11. Even though there is no relative disparity between the array of vertical lines, they are seen as being pulled forward in the region of the subjective square. There is no 'break' in the vertical lines if the pattern is viewed monocularly, yet it becomes obvious when viewed stereoscopically.

Suppose that this subjective square were to be seen as transparent, however. Then one might suspect that such stereo capture might not occur since the visual system could opt for the plausible interpretation that these lines continue uninterrupted behind the transparent surface. As such, the same configuration that is seen to lead to vigorous 'stereo capture' might not if it was slightly modified to yield the perception of a transparent surface. This can be accomplished by the simple addition of the 'colored' wedges to the pacmen, leaving the array of vertical lines intact. It should be clear from the upper stereogram of figure 11 that a transparent surface is perceived and no longer are the lines pulled forward as they are in the lower stereogram. Now they are seen as continuing behind the transparent surface. Again, subtle changes in

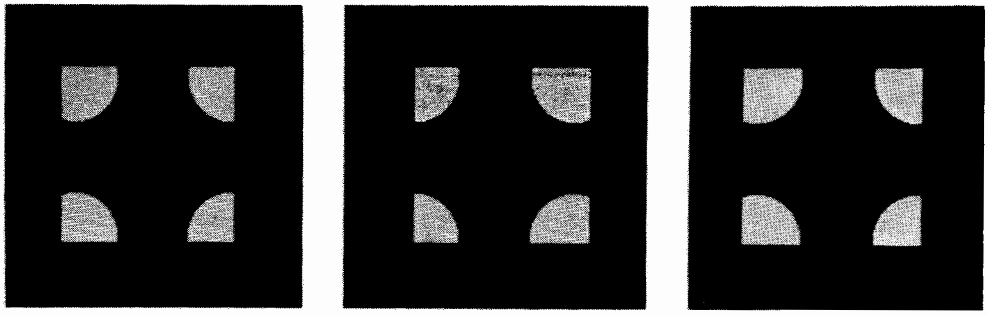


Figure 10. Reduced Varin configuration. This is the same as that seen in figure 6 except that the pacmen have been removed, only the filled wedges remain. Instead of seeing a transparent surface in front as in figure 6, one sees the wedges viewed through a square window. Even though the disparity relations of the wedges are the same here as in figure 6, the perceived depth of the region of the square is very different.

the configuration which give rise to changes in transparency can have clear effects on the perception of depth.

For our final demonstration of this series, we show that the conditions that lead to transparency can suppress otherwise robust subjective contours. For this point to be made, several stereograms must be compared. First, go back and examine figure 4. Recall that this was the first stereogram to show the importance of binocular disparity or perceived transparency. When the horizontal limb of the inner cross was in crossed disparity, one saw a transparent disk in front of a larger cross. Now fuse the stereograms seen in figure 12. Here we see a horizontal bar in front of a vertical bar. Also

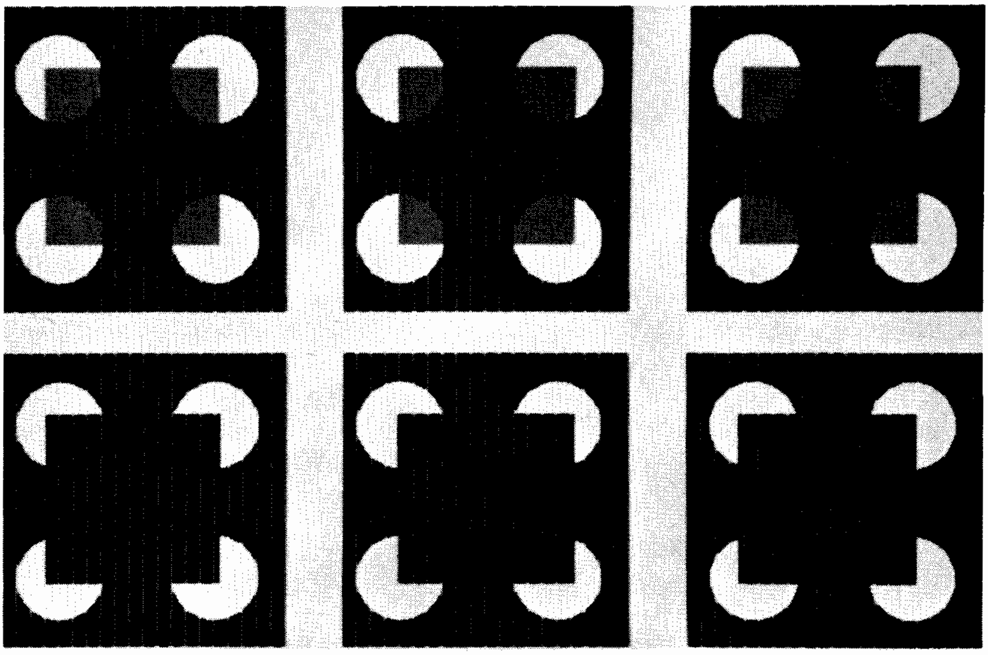


Figure 11. Transparency can block stereo capture. In the lower stereogram, we show the stereo capture phenomenon reported by Ramachandran and Cavanagh (1985). The central and nearer square 'captures' the background lines so that they also appear to be on the nearer surface. In the upper stereogram, the front surface is seen as transparent. Stereo capture is absent and one sees the lines as continuing behind the transparent surface.

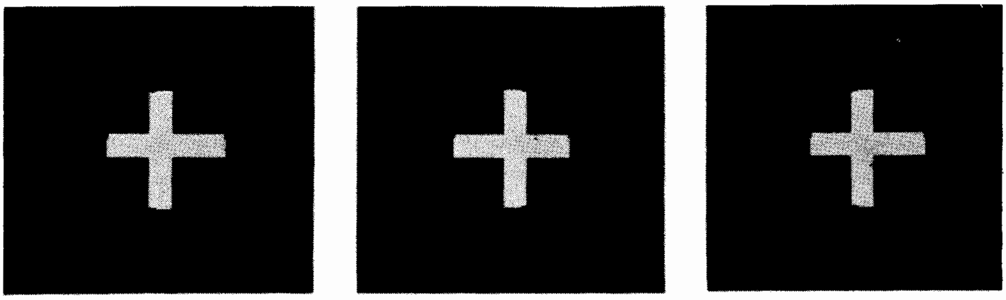


Figure 12. Aboliton of subjective contours by the triggering of perceived transparency. The observer should see a horizontal bar in front of a vertical bar. Associated with this perception is a horizontal subjective contour occluding the vertical bar. It should be noted that this cross is identical to the one shown in figure 4 except that the outer limbs have been removed. In figure 4 the same disparity relations do not lead to the same subjective contour because these are blocked by the appearance of transparency.

visible is a horizontal subjective contour completing the horizontal bar across an otherwise uniform luminance distribution. Of primary importance is the fact that the smaller cross in figure 12 is identical to the one seen in figure 4. Thus, each cross with identical disparity configurations gives rise to a very different perceptual interpretation of the scene. The simplest configuration (as shown in figure 12) gives rise to the perception of relative depth between horizontal and vertical bars plus an associated subjective contour. Yet, when the outer limbs of the cross are added (as in figure 4), the perception of transparency is dominant, suppressing local depth differences within the inner cross, also suppressing the subjective contour.

The demonstrations in this section suggest that *transparency mechanisms can determine depth* (figures 10, 11, and 12). Further, we have also shown that the *transparency mechanisms can suppress subjective contours*.

6 Role of luminance and chromaticity

Perhaps the most important finding to emerge from the early studies of transparency was the importance of relative luminance. Metelli (1974a; 1974b) outlined the basic luminance relations and most recently Beck (1986) has discussed these relations in terms of the functional interpretation of natural scenes. Metelli found that the object which is to be perceived as transparent must be of intermediate luminance relative to the object which is occluded and the background. The demonstrations that we have presented so far conform to these conditions. Thus the inner limb of the cross or the inner squares in figures 1, 4, 6, and 9 are of intermediate luminance with respect to the other image features and the background. It is Metelli's prediction that if the luminance of these regions is exchanged, transparency will generally shift to the region of intermediate luminance.

If one examines the stereogram in figure 13 where the luminance is reversed between the outer and inner limbs of the cross, a very different perception emerges. No longer do we see a transparent disk in front of a cross as in figure 4, but we may perceive a much larger transparent area which covers the outer limb of the cross, out of which is cut a central hole through which one can see the inner white cross unobstructed by any transparent surface. This shift in the location and shape of the transparent surface (from the central to the peripheral region) is consistent with Metelli's conditions mentioned above. The transparent surface overlies the region having the intermediate luminance. This demonstration has one additional implication of importance. It shows that luminance relations alone, independent of changes in the disparity of elements, are sufficient to change the perception of depth—the same

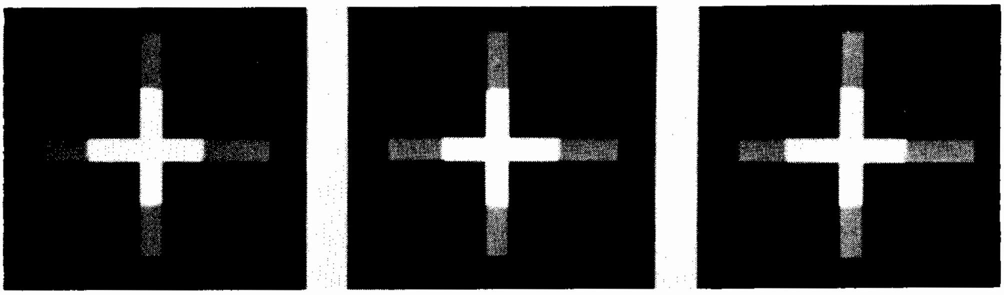


Figure 13. Ehrenstein configuration with a reversal of luminance relations between the inner and outer limbs of the cross. Now the transparent region in front is seen in front of the outer limb of the cross rather than the inner limb. Note that the disparity relations in this figure are identical to those seen in figure 4, only luminance is changed. Thus, luminance has a large role in dictating perceived depth.

implication as that of figures 10, 11, and 12. In figure 4, the region of central cross is seen as two surfaces, a transparent surface in front of a cross behind. In figure 13, where the luminances between the inner and outer cross are exchanged, there is no longer a closer object in the region of the inner cross but, instead, one perceives a larger transparent and closer surface surrounding this region.

We also examined the importance of chromaticity in the transparency illusion. First we found that it works for a wide variety of colors. Thus the central portion of the Ehrenstein cross or the inner wedges of the Varin configuration can be almost any color so long as they satisfy Metelli's luminance conditions (see plate 1a). More interesting, however, is the fact that both the occluder and the occluded object can be colored and the sense of transparency and color spreading still persists (see plate 1b). The transparency and color spreading in this condition are robust so that minimizing the difference in luminance between the two colors (the central cross and the outer limbs) did not abolish the effects easily. This combination of very different chromatic values and relatively similar achromatic values is of significance because it is very difficult to see how such a spectral distribution of colors would arise from a real-world scene. It would be improbable to find broadband filters in a real-world situation which could lead to the spectral distribution seen in plate 1b, yet we see a transparent filter nevertheless. It is also worth noting that the color of the central cross region 'seen' in plate 1b is the same as that in plate 1a, indicating that no perceived mixture occurs in the central cross region, even though this would be the implication of a 'filter' interpretation. Ware (1980) reported a similar set of observations in the Varin configuration without disparity.

7 Discussion

The primary approach in this work has been to use stereoscopic disparity as a tool to manipulate perceived depth, then to observe its influence in determining the perception on transparency, color spreading, and subjective contours. In addition to disparity, we also manipulated configurations and luminance relations, and noted that these had a major influence on transparency and color spreading as well. Under the various conditions where such a comparison was appropriate, we found that the perception of transparency always occurs whenever color spreading occurs (see figures 4, 6, 7, 9, 11, 12, and 13) but the opposite is not the case. Transparency can occur without neon color spreading (figure 8). Thus, transparency perception is a necessary condition for the emergence of neon color spreading, but not vice versa. Furthermore, we also found that the perception of transparency occurs only in cases where the transparent surface has disparity which indicates that it is in front, yet where there are indications that it occludes something in the more distant plane. Further, transparency occurs only when the luminance relationships are such that it allows an interpretation with filterings of light energy by a semitransparent surface in front. Thus, simply having the colored region in crossed disparity was not sufficient to obtain the transparency effect (see figure 9). Furthermore, the emergence of transparency and color spreading obeyed Metelli's luminance relationships, a constraint which is consistent with a transparent filter placed before a background object (the 'filter' interpretation). But again, this luminance constraint is meaningful only when the transparent surface is in front.

So the correlation between color spreading and transparency, and the clear implication of transparency as being related to an interpretation of a 3-D scene, argues rather forcefully for a common explanation of these phenomena. Neon color spreading as well as the perception of transparency cannot be understood if we confine our analysis to two dimensions. Neon color spreading arises as a consequence of how the visual system makes an interpretation of the probable 3-D scene from binocular images.

In addition, however, we also saw that transparency itself is not just the passive by-product of 'earlier' processes. We also presented a number of demonstrations which indicate that the luminance conditions that lead to the perception of transparency can profoundly alter depth and contour relations in a scene; changing a region ordinarily seen in front to one seen in back (see figures 10 and 13) or, perhaps even more dramatically, changing the local interpretation of an image patch from being interpreted as one bar occluding another to a cross seen behind a transparent disk (compare figure 4 with figure 12). The potential implications of these findings are significant because they suggest that a simple sequential activation of modules, say a depth module followed by a transparency module, cannot account for our findings.

7.1 *Intelligence and perception*

The results mentioned above, taken together with earlier findings by Redies and Spillman (1981) and Redies et al (1984) would seem to indicate that perception is 'intelligent' and that the assignment of depth and color are intimately related to how an observer might interpret a 3-D scene. Such a view has been espoused by Gregory (1970) and Rock (1983), who suggest that much of perception can be considered as a relatively higher-level cognitive inference. We do not deny that something akin to an inference is made by the visual system. We would like to stress, however, that the term 'inference' need not be restricted to the highest levels of analysis (see also Paradiso et al 1990). Inferences regarding transparency, for example, could be done by a relatively low-level set of autonomous simple computations with limited information (see Grossberg and Mingolla 1985).

This 'limited information' view is additionally supported by the existence of 'perceived' transparency even when the colors of the various patches in an image could not be realistically seen as arising from a physically plausible situation (plate 1b). Here, it is very difficult to conceive of a transparent filter (having relatively broadband spectral absorption) which would change green light to red light. Yet our visual system still sees the red region in plate 1b as transparent, as a filter in front of a green cross.

This finding with respect to color is reminiscent of the nonveridical perception of transparency reported by Beck (1986), although his case was achromatic. He systematically examined effects of relative luminance among stimulus patches in relation to constraints imposed by optics and found that the visual system implements some simple optical constraints. For example, "the overlaying of a transparent surface cannot change the order of the lightness values" (see also Metelli 1974a, 1974b). On the other hand, he also found some special cases where luminance relationship violated other, more quantitative optical constraints, and yet a clear perception of transparency was obtained; that is, human subjects sometimes perceive transparency which is *physically impossible*.

Transparency perception, therefore does not conform exactly to the laws of ecological optics, particularly in the case of color. If we were to program a computer to embody the nature of real objects, their reflectance and transmissivities, it might be expected to present us with a 'cannot compute' or 'error' message with the ecologically implausible chromatic relations in plate 1b. It appears, however, that our visual system is more robust and can provide an interpretation of physically impossible image data. This example indicates that our visual system provides an interpretation based primarily on luminance, largely ignoring the specifics of chromatic signals. This independence of some aspects of visual processing from chromatic signals has been reported previously (Gregory 1977; Ramachandran and Gregory 1978; Livingstone and Hubel 1987). As such, as argue that the system can function effectively by employing 'crude' tricks (Ramachandran 1985) or heuristics (Braunstein 1976), rather than performing a detailed and/or exhaustive interpretation of the scene with all of the information available.

7.2 *Interaction of separate feature representations*

Ever since the pioneering studies of Zeki (1974), growing emphasis has been placed on the possible existence of separate feature representations. It has been assumed that different functional streams might encode distinct aspects of an image and that these representations are highly segregated (Livingstone and Hubel 1987).

Results presented in this paper, however, suggest a close functional linkage between different features. One of the most dramatic effects reported here is the lability of color, varying in given image regions depending on depth relations. This suggests that at some level of extrastriate visual cortex, depth signals influence chromatic signals. Depth itself, however, can also be influenced by changing the relative luminance between regions or changing the surrounding configurations, leaving local disparity relations unchanged. This was seen in the comparison between figure 4 and figure 13: simple changes in the relative luminance of the center versus outer cross lead to very different depth and surface perception. Thus, there appears to be strong coupling between the dimensions of depth, color and lumimance, indicating interaction rather than segregation. So it is possible that the segregation of pathways seen in anatomical and physiological studies (DeYoe and van Essen 1985; Schipp and Zeki 1985; Livingstone and Hubel 1987) could be misleading if considered in isolation.

7.3 *Interaction via feedforward or feedback connections in cortex?*

Perhaps one of the most striking aspects of our finding taken as a whole is that the conditions that lead to the perception of transparency can in turn lead to drastic modifications of depth, color, and contour perception. Thus, rather than appearing to be a simple and passive end-point, the perception of transparency seems to have important perceptual consequences, modifying the seemingly more primitive processes of depth, color, and contour. Against a simple bottom-up viewpoint, the apparently 're-entrant' relation between the perception of transparency and its supposed more primitive antecedants suggests a link to the issue of feedforward versus feedback processing in cortical organization.

In supporting the feedforward idea, Marr (1982) suggested a possible principle for visual processing, the 'principle of least commitment'. The basic idea was that it would be inefficient for an earlier part of the visual system to make a decision regarding image data, only to have it reversed or revised later. Thus, earlier stages should refrain from making decisions on limited data. Implicitly criticizing the 'trigger feature' concept of Barlow (1972), Marr viewed the neurons in striate cortex as making measurements for later interpretation rather than as detectors of lines or edges. One consequence of such a view is that it tends to emphasize feedforward processing. Information from more peripheral regions of the visual system would converge centrally to provide greater completeness in terms of scene interpretation.

Although such a principle may be desirable and may have specific advantages under restrictive conditions, it appears that the visual cortex has the structure to do otherwise. Anatomical studies of the visual cortex, for example, do not indicate that there is a predominance of feedforward over feedback connections. In fact, for every forward projection there is almost invariably a concomitant back projection of comparable magnitude (van Essen 1983). Moreover, there appears to be an important difference between feedforward and feedback connections. While the feedforward connections preserve the columnar segregation of afferent inputs, the feedback connections from a given cortical target to its source do not. Segregated zones from V2 project to segregated zones in V4, generally preserving the general segregation of thin stripes, thick stripes, and interstripes in separate patches in V4 (DeYoe and van Essen

1985; Shipp and Zeki 1985). whereas the back projection from a given target zone in V4 is not limited to the specific regions of V2 from which it received its innervation (Krubitzer and Kaas 1989; Zeki 1990).

Such a substrate invites some comparison with the present results, particularly since color, subjective contours, and depth appear to have early and separate representation in area V2 (von der Heydt et al 1984, 1989; Hubel and Livingstone 1987), yet our results indicate that each can be influenced by higher-order aspects of scene interpretation, such as transparency. Thus, as an alternative to the simple notion of a feedforward convergence to yet another higher order cortical area, one must be open to the possibility that the back projections seen in visual cortical areas could mediate the modulation of more primitive signals depending on 're-entrant' signals from higher-level processing (see Krubitzer and Kaas 1989). If the back projections of the sort suggested here play such a functional role, the signaling of such 'earlier' neurons might be susceptible to the manipulations described in this paper. So in terms of thinking about future neurophysiological experimentation in alert primates, one wonders whether it might be possible to suppress the response to stereoscopically induced subjective contours, or to change chromatic or depth processing (as early as V2) by arranging the configuration so that it is seen or not seen as a transparent surface.

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Correction of plate 1 (note also that figure 9 is upside down)