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Part boundaries alter the perception of transparency

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The perception of transparency is a remarkable feat of human vision: A single stimulation at the retina is interpreted as arising from two (or more) distinct surfaces, separated in depth, in the same visual direction. This feat is intriguing since physical transparency is neither necessary nor sufficient for phenomenal transparency. Many conditions for phenomenal transparency have been studied, including luminance, chromaticity, stereo depth, apparent motion, and structure from motion. Figural conditions have also been studied, primarily by Gestalt psychologists (Kanizsa, 1979; Metelli, 1974), resulting in descriptive laws. Here we refine, and make precise, these laws using the "genericity principle," and the "minima rule" for part boundaries. We report experiments which support the psychological plausibility of these refinements. They suggest that the formation of visual objects and their parts is an early process in human vision, which can precede the representation of transparency.

Introduction

In Figure 1a we see two opaque gray rectangles, one on a dark background, and the other on a light background. If the two gray rectangles are moved, so that their edges coincide with each other and with the lightness border (as in Figure 1b) we now see, not two opaque gray rectangles as before, but a single large transparent filter, in front of the divided background. This shows that physical transparency is not necessary for phenomenal transparency. Also, in Figure 2a, we do not see transparency even though this display might be produced by a transparent filter placed over the bicolored background. Thus physical transparency is not sufficient for phenomenal transparency.

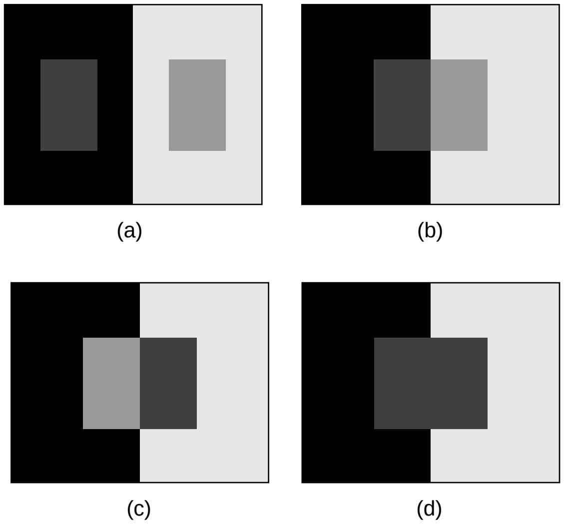
(a) (b) (c) (d)

Figure 1. Luminance conditions for transparency.

What conditions determine when transparency will be seen? The most extensively studied conditions for phenomenal transparency are those involving achromatic luminance Metelli, 1974; Kanizsa, 1979; Beck, Prazdny, & Ivry, 1984; Metelli, Da Pos, & Cavedon, 1985; Gerbino, Stultiens, Troost, & Weert, 1990); and these have also been extended to the chromatic domain (Da Pos, 1989; D'Zmura, Colantoni, Knoblauch, & Laget, in press). For example, if the two gray rectangles in Figure 1b are interchanged (as in Figure 1c), or if both gray rectangles are given the same luminance (as in Figure 1d), then the perception of transparency is lost. In addition to luminance conditions, it has been shown that the perception of transparent surfaces interacts with stereo depth ((Nakayama, Shimojo, & Ramachandran, 1990); (Nakayama & Shimojo, 1992)), subjective contours (Nakayama et al., 1990; Cicerone & Hoffman, 1991), apparent motion (Cicerone & Hoffman, 1991; Cicerone, Hoffman, Gowdy, & Kim, 1995; Shipley & Kellman, 1994; 1997), and structure from motion (Kersten, Bülthoff, Schwartz, & Kurtz, 1992).

In displays like Figure 1 it is clear that, apart from luminance conditions, certain properties of shape must also be satisfied in order for transparency to be seen. For example, in Figures 1a, 2a, and 2b, transparency is not seen.

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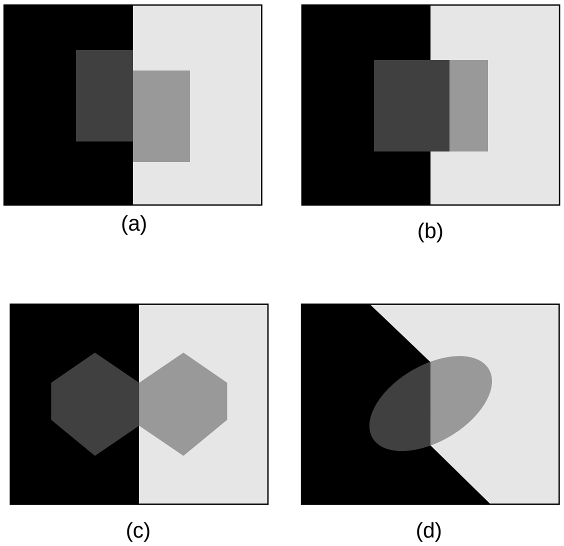

Figure 2. Kanizsas topological condition (a,b); and Kanizsa and Metellis condition of discontinuity of direction (c,d).

These displays violate Kanizsa's (1979) "topological condition": The two gray regions that are to form the transparent surface must be in contact with each other, and each must make contact with only one of the two background regions. A figural condition suggested by Kanizsa (1979) and Metelli (1974) is "discontinuity of direction". Examples, by Kanizsa (1979, p.158–161), of discontinuity of direction are shown in Figures 2c and d. As these displays indicate, by discontinuity of direction, Kanizsa meant two things: discontinuity in the direction of the contour of the filter (as in Figure 2c), and discontinuity in the direction of the line dividing the background (as in Figure 2d). Kanizsa gave Figure 2c as an example where transparency is blocked, and Figure 2d as an example where transparency is not blocked, by the discontinuity of direction. In this paper, we consider only the case of discontinuity of the filter. The experiments we report here suggest two explanations, based on more recent work in vision, that can be cast in precise mathematical terms, and that refine the discontinuity explanation. The first is more general, and is based on the principle of genericity (e.g., Binford, 1981). The second is based on the "minima rule" (Hoffman & Richards, 1984) for parsing visual shapes, and on a part-salience rule that builds on the minima rule (Hoffman & Singh, 1997). These two explanations are not mutually exclusive, but complement each other.

The Genericity Principle

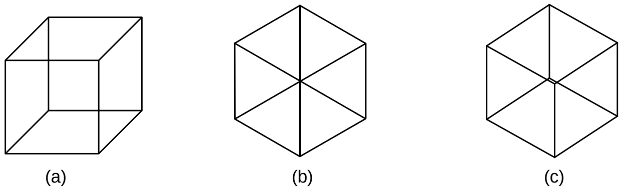

Figure 3. The principle of genericity.

Interpretations made by human vision about the visual environment are typically underconstrained by the information available at the retinal images: Countless interpretations are always consistent with any given image or set of images. To deal with this problem, human vision uses various constraints on possible interpretations, and is thus able to reach unique or nearly unique interpretations. The principle of genericity provides one powerful such contraint. In its simplest form, this principle says to reject "unstable" interpretations of visual stimuli. An unstable interpretation is one which, if perturbed slightly, would lead to a qualitative change (e.g., a change in the topological or first order differential structure) in the image. As an example, consider the "Necker cube" in Figure 3a, which we readily perceive as a cube in three dimensions. In Figure 3b, however, the perception of a cube is lost; the figure looks more like a flat pinwheel. In fact, this image is also the projection of a cube, albeit from a special viewing position–one in which two opposite vertices of the cube are perfectly aligned. This viewing position is nongeneric, however, because even a slight change in the viewing position would change the topological structure of the image: For example, the image in Figure 3c has seven connected regions, whereas the image in Figure 3b has six. Because interpreting Figure 3b as a cube requires assuming a nongeneric (i.e., unstable) viewing position, human vision rejects this interpretation, and we therefore see Figure 3b as flat.[1]

The principle of genericity has been applied, successfully, to provide theories of various visual capacities, including the 3D interpretation of line drawings (Binford, 1981; Lowe & Binford, 1985), the perception of subjective contours (Albert & Hoffman, 1995; in press), the perception of object parts (Hoffman & Richards, 1984; Biederman, 1987; Hoffman & Singh, 1997), the perception of shape from shading (Freeman, 1994), and the phenomenon of color constancy (Brainard & Freeman, 1997). It has also been incorporated into formal Bayesian models of visual perception (Freeman, 1996).

To see the role of genericity in the perception of transparency, consider the display in Figure 4a in which we perceive an circular transparent filter over a bicolored background. In Figure 4b, two concave cusps have been introduced that fall precisely on the lightness border. Now the

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[1] One might argue that it is the symmetry of the pinwheel interpretation that is responsible for the perceived flatness. But one gets the same effect with nonregular solids—for which the flat interpretation is not symmetric. Hence symmetry fails to provide a general explanation of the phenomenon (see Kanizsa, 1979, p.105–106; Albert & Hoffman, 1995).

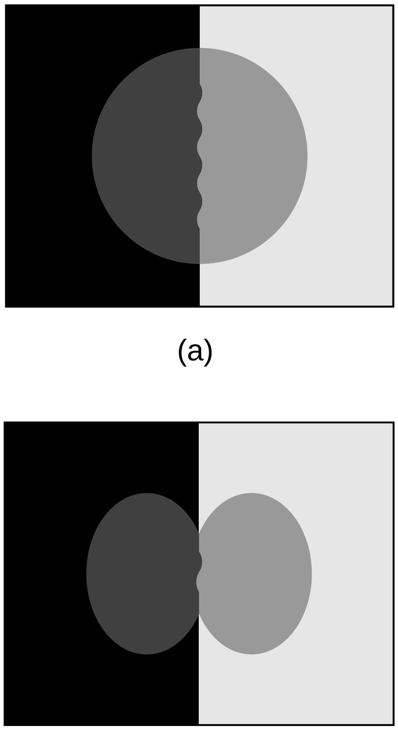

Figure 4. The role of genericity in the perception of transparency.

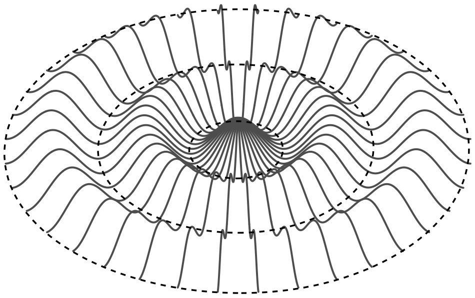

Figure 5. The cosine surface.

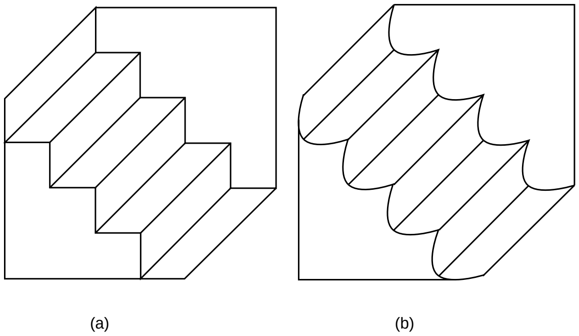

Figure 6. A demonstration of part salience.

perception of transparency is greatly reduced. According to the genericity explanation, if there were a transparent filter in front of the divided background, it would take a special viewing position to make the extrema of curvature on the filter align precisely with the lightness border; hence the interpretation of the transparent filter is nongeneric. Therefore the luminance change should be interpreted as a reflectance change, i.e., due not to transparency but due to different surfaces.

The Minima Rule

There is now growing evidence that human vision represents the shapes of objects in terms of component parts, and the spatial relationships between these parts (Marr & Nishihara, 1978; Hoffman & Richards, 1984; Biederman, 1987; Braunstein, Hoffman, & Saidpour, 1989; Baylis & Driver, 1995a, 1995b; Hoffman & Singh, 1997). From a computational perspective, part-based representations of shape provide an efficient way to deal with occluded objects, and with articulated objects that do not have fixed shapes—both of which are problems for traditional theories of object recognition, such as template theories and Fourier models. Indeed, recent experimental evidence suggests not only that human vision parses shapes into parts, but that it does so quickly, perhaps preattentively (Baylis & Driver, 1995a, 1995b; Driver & Baylis, 1995; Hoffman & Singh, 1997; Singh, Seyranian, & Hoffman, in press).

Hoffman & Richards (1984) have argued that human vision uses general computational rules to parse objects into parts. Their "minima rule" defines part boundaries. Because it is expressed solely in the language of differential geometry, it applies quite generally. For a silhouette, the minima rule gives negative minima of curvature as boundary points on the contour of the silhouette. For a 3D object, it gives loci of negative minima of the principal curvatures as boundary curves on the surface of the object. The "cosine surface" in Figure 5 nicely demonstrates the minima rule. Here we see circular hills separated by valleys. The boundaries between one hill-shaped part and the next are marked by dashed contours—these are the negative minima of the principal curvatures. If you turn the figure upside down, the figure-ground reversal changes the negative minima to positive maxima, and vice versa. This causes the part boundaries to shift to the new negative minima, and so you now see new parts. The dashed contours which before sat between hills now sit on top of hills.

Hoffman & Singh (1997) proposed a part-salience rule: sharper negative minima of curvature are more salient part boundaries. As an example, consider the Schröder staircase in Figure 6a. This can be seen either as a normal ascending staircase (the "staircase below" interpretation), or as a strange inverted staircase (the "staircase above" interpretation). One usually prefers to see the staircase below. But in

Figure 6b, the staircase has been altered so that the above interpretation has more salient part boundaries than the below interpretation. As a result, the above interpretation has more salient parts, and we therefore tend to see the staircase above in Figure 6b, despite the usual preference to see figure below.[2]

To see the role of part boundaries in the perception of transparency, consider again the display in Figure 4b. According to the minima-rule explanation, the sharp negative minima of curvature on the filter indicate two distinct parts. Hence the change in luminance at the part boundaries is interpreted not as transparency, but as different parts of an object having different reflectances. The difference between the part-boundary and the genericity explanations is that the part-boundary rule predicts a difference between positive maxima and negative minima (roughly, convex and concave extrema) of curvature, whereas the genericity principle does not. Specifically, the minima rule predicts that the presence of negative minima should impair the perception of transparency more than the presence of positive maxima of comparable strength.

EXPERIMENTS

We ran two experiments to demonstrate the genericity effect and the minima-rule effect, in the perception of transparency. The first experiment pits filters with no extrema (see Figure 4a) against those with extrema (see Figure 7) aligned with the lightness border, to get at the genericity effect; and it pits negative minima against positive maxima to get at minima-rule effect. In addition, it looks at the effect of smoothing and turning angle at the extrema—in light of Hoffman & Singh's (1997) theory of part salience mentioned above. The second experiment provides further support for the genericity explanation, by looking at the effect of displacing the curvature extrema of the filters from the lightness border (see Figure 9).

Experiment 1

Method

Subjects. The subjects were eight graduate students at UCI, naive to the purposes of the experiment.

Stimuli. The stimuli were 25 displays like the ones in Figure 7. The CIE coordinates and luminance values of the four regions were as follows: Lightest gray ($x = .273, y = .269$, luminance $= 46.2 cd/m^2$); Light gray ($x = .268, y = .264$, luminance $= 23.0 cd/m^2$); Dark gray ($x = .248, y = .234$, luminance $= 3.59 cd/m^2$); Black (luminance $= 0 cd/m^2$). The displays were viewed at a distance of 0.5 meter and each was about 15 degrees tall and 20 degrees wide. One display had a circle as the transparent filter (see Figure 4a). Twelve displays had negative minima of curvature, that were perfectly aligned with the lightness border (as in Figures 7a–d). Twelve displays had positive maxima of curvature, perfectly aligned with the lightness border (as in Figures 7e–h). A wiggle was drawn down the middle of the lightness border to suppress the perception of a crease in 3D, which is striking in the stimuli with strong negative minima and positive maxima. In a pilot study, subjects reported that this 3D crease interfered with their judgment of transparency. The length of the wiggle was adjusted in each display so that it stopped at about 1 degree of visual angle from the $X-/\psi-$junctions.

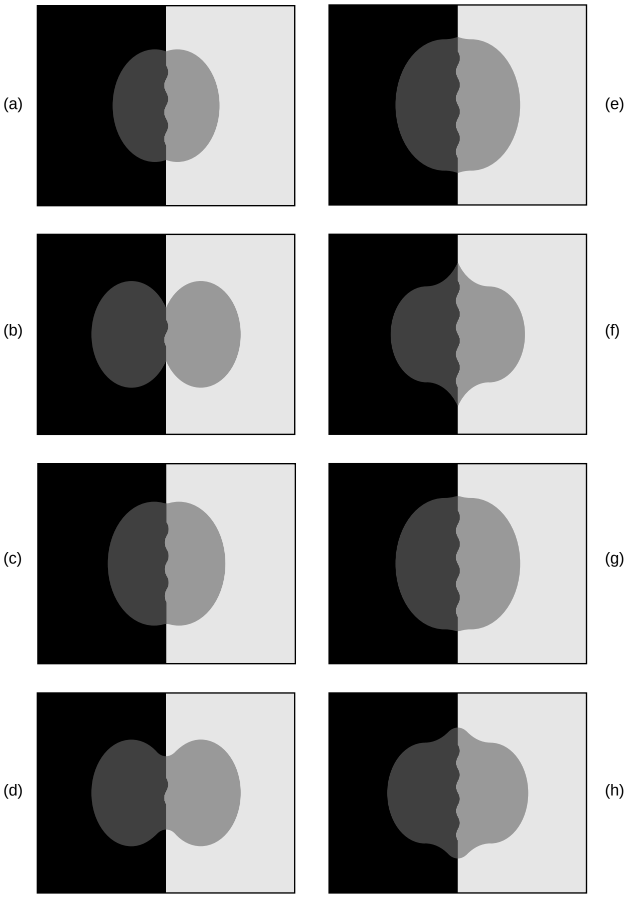

Figure 7. Eight of the stimuli used in Experiment 1.

Design. There were three independent variables: sign of curvature at the extrema, turning angle at the extrema, and level of smoothing at the extrema. All factors were run within subjects. The sign of curvature had two levels: positive maxima of curvature, and negative minima of curvature. The turning angle at the extrema had four levels, labeled 1, 2, 3, & 4 (defined below). The smoothing had three levels: cusp, low level of smoothing, and high level of smoothing. (Figure 7 shows eight of the stimuli used.) All stimuli were part of this $2 \times 4 \times 3$ factorial design, except for the

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[2] This argument is based on Hoffman & Singh's (1997) *Hypothesis of Salient Figures:* Other things being equal, human vision prefers that assignment of figure and ground which leads to the figure side having the more salient parts.

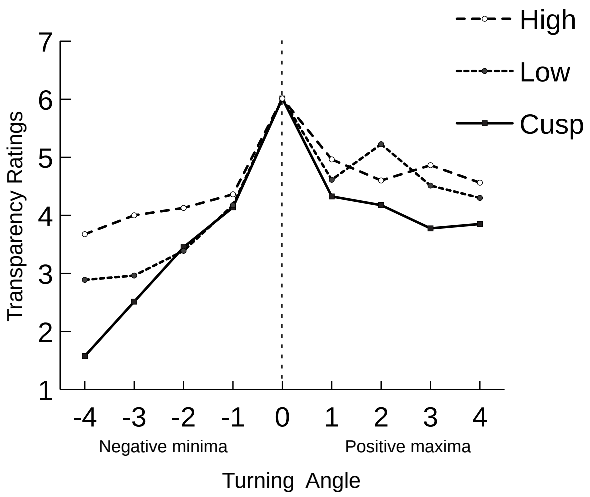

Figure 8. Results of Experiment 1.

stimulus with the circle—for which smoothing is inapplicable. Hence there were a total of $24+1=25$ stimuli. Each stimulus was presented ten times, resulting in a total of 250 experimental trials. These were preceded by 50 practice trials. Whether the more luminous side of the bicolored background appeared on the left or on the right of each display was counterbalanced.

For the stimuli with cusps, the four levels of turning angle were (in degrees) 42, 72, 102, and 132. Their smoothed versions were created as follows: The cusp version was taken, and a region of the contour around the cusp was replaced with an arc from the tip of an ellipse. The dimensions of this ellipse were 1.5 x 1.1 degrees of visual angle in the low smoothing case, and 3.1×2.3 degrees of visual angle in the high smoothing case.

Apparatus. The figures were displayed on a 1024 by 768 monitor by a Macintosh Quadra computer using the SuperLab program. Subjects used a keyboard to respond.

Procedure. Subjects were instructed that, on each trial, they would see a figure composed of four regions with different shades of gray. They were to judge whether the two regions in the center were transparent, using a scale from 1 to 7, with 1 corresponding to "No transparency, I see 4 opaque regions," 4 corresponding to "Moderate transparency," and 7 corresponding to "Strong transparency, I see a gray filter over a black and white background." The displays were presented in random order. Each trial consisted of a fixation dot for 500 milliseconds, a transparency display for 2 seconds, and then a response screen which asked the subject to rate the transparency of the display from 1 to 7. This screen remained until the subject responded.

Results and Discussion

Figure 8 shows the results of the first experiment. Transparency ratings are significantly lower for both the negative minima and positive maxima cases, as compared to the circle case, $F(1,7) = 177.32, p < 0.0001$. This supports the genericity explanation, since a transparent interpretation of a display in which extrema (positive maxima or negative minima) of curvature align with the lightness border would be nongeneric.

The results also support the minima-rule explanation, because the transparency ratings are significantly lower for negative minima, than for positive maxima, $F(1,7) = 30.048, p < 0.001$. As mentioned above, this is not predicted by the genericity explanation. Furthermore, there is a main effect of the smoothing level, $F(2,14) = 15.353, p < 0.0005$: Transparency ratings are lower for cusp extrema than for smooth extrema. This supports Hoffman & Singh's (1997) theory of part salience, according to which cusp boundaries are more salient than smooth ones. There is also a main effect of turning angle, $F(3,21) = 9.635, p < 0.0005$, which is another factor in the theory of part salience, i.e., larger turning angles are indicative of more salient part boundaries.

In sum, these results show that the "discontinuities" explanation of Kanizsa and Metelli can be refined in two ways:

1. Neither tangent discontinuities, nor discontinuities of higher derivatives, are necessary to block the perception of transparency because the ratings of transparency go down even when the extrema of curvature are smooth. In other words, in order to have a loss of phenomenal transparency, it is sufficient to have strong negative minima, or positive maxima, of curvature that align with the lightness border, even if these extrema have continuous higher-order derivatives.

2. The discontinuities explanation does not predict a difference between negative minima and positive maxima of curvature. The minima rule does predict this difference.

Experiment 2

The purpose of the second experiment was to further support the genericity explanation, by showing that it is indeed the precise alignment of the extrema of curvature with the lightness border that leads to the decline in transparency ratings. We predicted that if the extrema were displaced from the lightness border, then transparency ratings would increase.

Method

Subjects. The subjects were eight graduate students at UCI. They were naive to the purposes of the experiment.

Stimuli. The stimuli were 18 transparency-type displays, that had the same respective luminance values as the displays in Experiment 1. The displays were viewed at a distance of 0.5 meter and each was about 15 degrees tall and 20 degrees wide. Six of the displays were taken from Experiment 1, namely, the six displays with the most extreme turning angles (both positive and negative). These six displays were then modified by displacing, by two different amounts, the

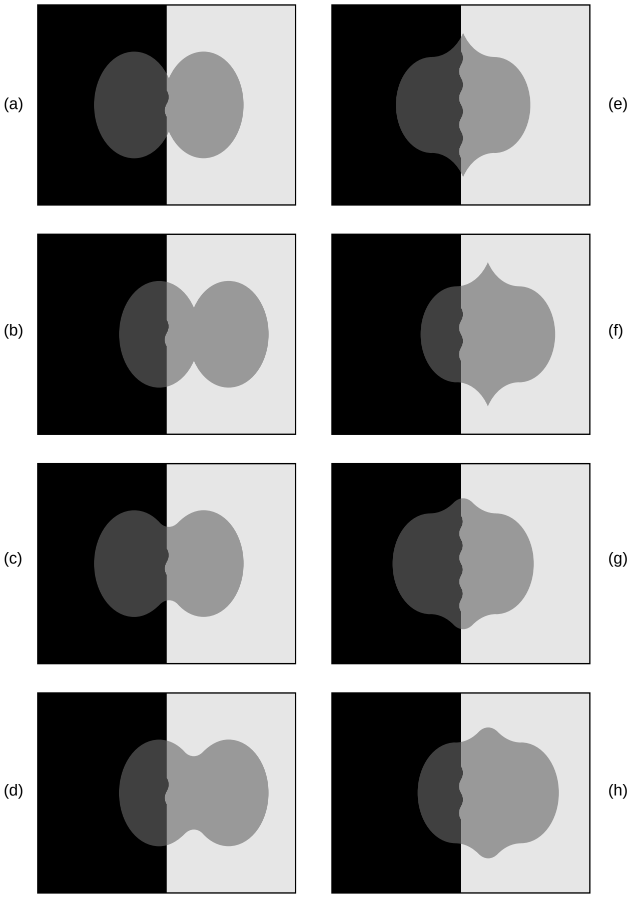

Figure 9. Eight of the stimuli used in Experiment 1.

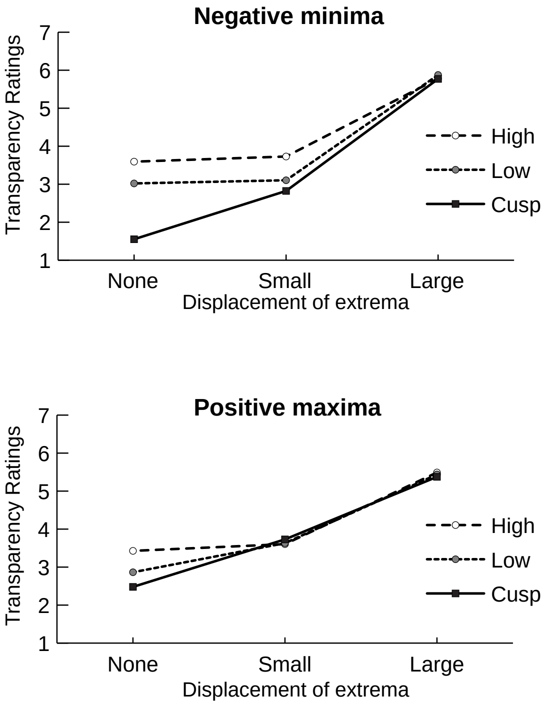

Figure 10. Results of Experiment 2.

extrema of curvature from the lightness border. The “small” displacement was a displacement of 0.25 degrees (see Figures 9a, 9c, 9e and 9g), and the “large” displacement was a displacement of 2 degrees (see Figures 9b, 9d, 9f and 9h).

Design. There were three independent variables: sign of curvature at the extrema, level of smoothing at the extrema, and the displacement of the extrema from the lightness border. The sign of curvature had two levels: positive maxima of curvature, and negative minima of curvature. The smoothing had three levels: cusp, low level of smoothing, and high level of smoothing. And the displacement had three levels: zero displacement, small displacement, and large displacement. This formed a $2 \times 3 \times 3$ factorial design. All variables were run within subjects. Each display was presented ten times, resulting in a total of 180 experimental trials. These were preceded by 36 practice trials.

The following variables were counterbalanced: (i) whether the more luminous side of the bicolored background appeared on the left or on the right of the display, and (ii) whether the extrema were displaced to the left or to the right of the line dividing the bicolored background.

Apparatus. Same as in Experiment 1.

Procedure. The instructions were precisely the same as in Experiment 1. The displays were presented in random order. Each trial was structured the same way as in Experiment 1.

Results and Discussion

Figure 10 shows the results for the second experiment. As predicted, there was a main effect of the level of displacement, $F(2,14) = 34.946, p < 0.0001$. In fact, for displays with “large” displacements, mean ratings came back up almost as high as the best ratings in Experiment 1 (i.e., for the display with the circle). There was also a main effect of smoothing, $F(2,14) = 9.194, p < 0.003$, but no main effect of the sign of curvature, $F(1,7) = 0.131, p > 0.7$.

There was a significant interaction between smoothing and sign of curvature, $F(2,14) = 4.774, p < 0.03$. Post hoc analysis revealed that, for displays with smooth extrema, transparency ratings were not significantly different between positive maxima and negative minima. However, they were significantly different for displays with cusps, with higher transparency ratings for positive maxima.

There was also an interaction between smoothing and displacement of extrema, $F(4,28) = 17.956, p < 0.0001$. Post hoc analysis revealed that, for large displacements, there was no significant effect of smoothing level, but for zero and small displacements, the ratings for the cusp displays were significantly lower than the ratings for the smoothed displays.

These results confirm the predictions of the genericity principle: It is indeed the the precise alignment of the ex-

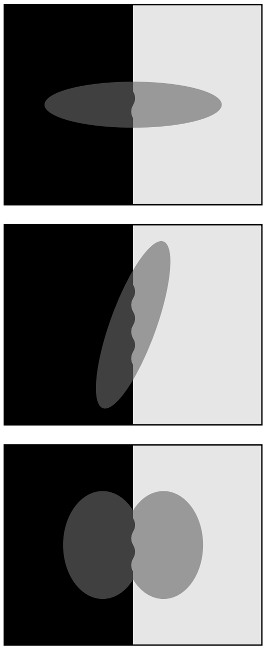

Figure 11. The three stimuli used in the control experiment.

trema of curvature with the lightness border that is responsible for the decline in transparency ratings.

An alternative hypothesis

An alternative “angle hypothesis” might be advanced to explain our results. The role of $X - /\psi-$junctions is well-known in the transparency literature (see, e.g., Kersten, 1991). It might be argued that the strength of perceived transparency depends not on the genericity principle and the minima rule, but rather on the angle between the filter contour and the lightness border (dividing the bicolored background) at each $X - /\psi-$junction. For example, in Figure 4a, the filter contour is orthogonal to the lightness border whereas, in Figure 4b, the filter contour meets the lightness border at a sharp angle—and it is perhaps this difference in angle that is responsible for the results obtained in Experiments 1 and 2.

Recall, however, that the results of Expriment 1 showed a significant difference between displays with negative minima and positive maxima of curvature, even though the angle magnitudes were controlled. For example, displays with negative minima cusps were consistently rated lower in transparency than the corresponding displays with positive maxima cusps—even though the angles between the contour and the lightness border were the same in both cases—see Figure 8. This shows that an explanation based on the angle hypothesis is insufficient to explain our results.

However, to directly test the angle hypothesis, we ran a control experiment using the three displays shown in Figure 11. The first display has an ellipse that is horizontally oriented (so that its contour is orthogonal to the lightness border), the second has an ellipse that is oriented at an angle (so its contour makes an angle of 30 degrees with the lightness border), and the third is a version of the “cusp negative minima” stimuli used in Experiments 1 and 2—with the constraint that the contour makes an angle of 30 degrees with the lightness border. All luminance values were the same as in the first two experiments. We counterbalanced two variables: whether the darker side appeared to the left or to the right, and whether the slope of the oblique ellipse was positive or negative.

Five subjects performed the same transparency rating task as in the first two experiments. We found a significant effect of display type, $F(2,8) = 26.74, p < 0.001$. Subjects consistently gave high ratings to the displays with the horizontal ellipse (mean = 5.15) and the oblique ellipse (mean = 6.23)—despite the difference in angles, and they consistently gave low ratings to the display in which the negative minima were aligned with the lightness border (mean = 1.83)—even though the angles for this display were the same as those for the display with the oblique ellipse. Post-hoc analysis revealed that the mean transparency ratings for the displays with the horizontal ellipse and the oblique ellipse did not differ significantly from each other, but did differ significantly from the display with the negative minima. This disconfirms the angle hypothesis and supports the genericity and minima-rule hypotheses.

Conclusions

We have proposed that the genericity principle, the minima rule, and a part-salience rule, provide a rigorous refinement of the gestalt figural conditions for the perception of tranparency. The experiments reported here support the psychological plausibility of these refinements.

The experiments also support the idea that human vision constructs various properties of visual objects in a highly coordinated fashion (Hoffman, in press; Singh & Hoffman, 1997). When the central regions in transparency-type displays are seen as a one-part object, they are perceived as being transparent and having uniform reflectance, but when they are seen as two parts of an object, they are perceived as being opaque with the two parts having different reflectances.

The experimental results suggest that the formation of visual objects and their parts can precede the representation of transparency. This may be surprising because transparency seems to be such a basic visual property. However, there is now psychophysical evidence which suggests that part formation is an early visual process (Hoffman & Singh, 1997), and possibly preattentive (Baylis & Driver, 1995a, 1995b; Driver & Baylis, 1995). So it is perhaps not surprising to find that other visual properties such as transparency depend on it.

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