Illusory contours and stereo depth*

R. L. GREGORY and J. P. HARRIS

*Brain and Perception Laboratory, Department of Anatomy, The Medical School
University of Bristol, Bristol BS8 1TD, England*

A theory for illusory contours, which fill gaps in certain figures, is proposed and subjected to an experimental test. We suggest that nearer masking objects are perceptually postulated to "account" for gaps when these are unlikely. The experiment shows that when stereoscopic depth information incompatible with this "perceptual hypothesis" is presented, the illusory contours are reduced in intensity or disappear.

Interest has recently been revived in the significance of stimulus figures that produce illusory contours (Gregory, 1972a; Coren, 1972), a phenomenon known since at least the beginning of this century (Schumann, 1904). A dramatic example is that produced by Kanizsa (1955) (Fig. 1), in which an illusory triangle may be observed, with its corners in the blank sectors of the three disks. This triangle appears to have sharply defined edges and to be of enhanced brightness compared with the white "ground."

There have been reports of such contours in stereoscopic displays for which each retinal image is not sufficient (Lawson & Gulick, 1967). Coren (1972) has linked the phenomena by suggesting that features of such two-dimensional displays as Fig. 1 provide depth cues in some way important for the effect. A somewhat related idea was put forward by Gregory (1972a, b), who suggested that such depth cues might produce the effect by providing perceptual evidence for "postulating" a masking object partially hiding the given figure to "account" for its gaps. This is a cognitive type of explanation, following from the general notion that perceptions are logically similar to hypotheses in science, which, like perceptions, are based on, but are never determined by, the available data. We suppose that in perception, limited sensory data are used to postulate hypotheses—perceptions—exceeding what is given, and also that accepted hypotheses may set what is regarded as data in a given situation (Gregory, 1970a, b, 1973). This will be taken up briefly later in this paper.

The following kinds of explanation have been or might be suggested for this effect:

(1) As an instance of the Gestalt principle of "closure," an explanation favored by Schumann (1904), Kanizsa (1955), and Pastore (1971). Thus, the "completion" of the illusory triangle by visual mechanisms leads to a "better" percept. However, it has been shown (Gregory, 1972b) that illusory figures can be created having concave sides, which are not "good" in the Gestalt sense.

(2) By supposing that the edges of the sectors and the ends of the lines of the broken triangle trigger cortical

"line detector" cells (Hubel & Wiesel, 1962). As has been pointed out (Coren, 1972; Gregory, 1972b), a broken line (or broken triangle as in Fig. 2) does not produce an illusory contour, although adding three dots, as in Fig. 3, does produce such a contour. This "negative" observation is important, for a theory based on triggering "line detectors" would surely predict illusory contours filling the gaps between the broken lines, rather than between the dots as observed. Lines should be powerful "trigger features," and the gaps between the dots are greater than the gaps between the given lines. We thus rule out a simple "triggering-of-line-detectors" explanation for these illusory contours.

The visual system has the constant problem of "deciding" what objects are present in the visual field, from available patterns of stimulation at the eye or other information. Distant objects are often partially masked by nearer objects, so that a gap may be an indentation in an object or it may be due to masking by a nearer object. Gaps given by masking must be important evidence for the presence of nearer objects: In the absence of texture, it may be the only evidence

Fig. 1. Illusory triangle with apices in the blank sectors of the disks. (After Kanizsa, 1955.)

*Figure 4 was drawn by G. Brown. We are grateful to our colleagues for their help and discussion, and thank the Medical Research Council for financial support.

Fig. 2. Broken triangle—which does not produce illusory contours.

Fig. 3. Illusory triangle—with apices at the dots.

available. We should expect *absence* of stimulation to be accepted as evidence of a nearer masking object when it is unlikely to be a physical gap in a viewed object.

It is evident that the lined up sectors of the three disks would be economically accounted for by the postulate of a triangularly shaped occluding object. We

suppose that the three dots provide further evidence of such an object—in this case, the corners of a nearer triangle—which would account for the gaps by masking.

To test the general notion that these illusory contours and regions are postulated masking objects, we have added depth information contradictory to the “nearer-masking-object hypothesis.” Using a stereoscopic display, we forced the dots behind the broken-line triangle. If they are accepted as lying behind the triangle, they should no longer provide evidence for a nearer masking object—so, on our theory, the illusory contours should cease to appear. If the dots were displayed in front of the broken triangle, we should expect the contours to be maintained, but to come forward with the “stereo displayed” dots, which would now delineate a still nearer masking object. Neither the Gestalt account nor the feature-detector hypothesis appear to predict that the direction of this depth difference should affect the illusion, though possibly they could predict a diminution with forward or backward depth imposed on the dots.

EXPERIMENTAL METHOD

Two circular back-projection displays, with 18-in. horizontal separation between their centers, were formed by covering 7-in.-diam holes in matte black opaque screens with translucent Perspex. Behind each of these screens was a shadow projection device. The left-hand display presented a pair of stereoscopic shadow images (Gregory, 1964, 1970c; Lee, 1969) by light from two point sources horizontally separated by 2½ in. and separately presented to the eyes by cross-polarization. The sizes of the shadow images were held constant for any distance, by collimating the point sources with a large (10-in.) surface-silvered parabolic mirror. The design of this stereo off-axis collimating system is shown in Fig. 4. A broken triangle was formed with black opaque tape on a clear Perspex sheet placed immediately behind the screen. A second clear Perspex sheet, with three opaque dots mounted on it, was suspended from a track, by means of which it could be moved (with a motor drive) to selected distances behind the projection screen. The O, wearing 90-deg opposed Polaroid spectacles, fused the two disparate shadow images to perceive the dots and broken triangle at different distances, corresponding to their separation in the

Fig. 4. Diagram of the stereo collimating system used to present the broken triangle and dots, at different relative depths.

apparatus. Reversal of the Polaroids reversed the disparity to the eyes, and so switched the relative distances of the dots and broken triangle.

In the right-hand comparison display, a plane mirror reflected the light from two similarly separated but unpolarized point sources. A single clear Perspex sheet, with the whole figure mounted on it, was suspended behind the screen and in contact, to prevent double shadows from the separation of the point sources. The intensities of the two polarized point sources in the stereo display were matched using an S.E.I. photometer. At the beginning of the test session with each S, small adjustments were made to the intensity of the comparison display until the two displays appeared of equal brightness, to compensate for small directional effects. This "comparison" display was then left unchanged throughout the experimental session. The S, wearing Polaroid spectacles, sat 8 ft 6 in. from the displays, on a line which was a continuation of the optical axis of the "test" stereo display. Twelve different viewing conditions were used. For each orientation of the Polaroids, the movable Perspex plate on which the dots were mounted was presented in the same plane as the broken triangle, or at distances of 1 cm through 5 cm in 1-cm steps. These conditions were presented once in randomized order, and the S was instructed to close his eyes while the display was changed. For each condition, the S was first asked to report whether the dots or the triangle were the nearer, or whether they lay at the same distance. The S was then asked to judge how the illusory contours, and brightness, compared in the two displays. A forced choice technique was used, the permitted responses being: "enhanced" in the stereo display, "diminished," or "the same." Separate judgments were obtained for each phenomenon examined. Twelve Ss, eight male and four female, who were either medical students or technicians, were tested individually. Two additional Ss, who had inadequate stereo vision, did not complete the experiment. It was found that normal stereoscopic vision is necessary for the effects to be described.

RESULTS AND DISCUSSION

The histograms in Fig. 6 show the distributions of responses for the various stimulus conditions. An estimate of the reliability of the Ss' judgments can be obtained by examining the responses in the situation where the two parts of the figure were objectively on the same plane. One would expect most of these judgments to be that the illusory effects were identical in both displays. For this condition, 18 of the 24 judgments of the illusory contours were that they were the same in the two displays, 4 that they were enhanced in the stimulus display, and 2 diminished. Of the "enhanced" judgments, 2 occurred when the S perceived the dots as "somewhat in front of" the broken triangle. The

Table 1
Reported Appearance of Illusory Contours

	Enhanced	Diminished	Same
Dots stereoscopically in front	43	5	12
Dots stereoscopically behind	8*	48*	4†

Note—The entered numbers are the totals of each of the three permitted judgments, pooled for all "in front of triangle" and all "behind triangle" displacements of the dots. Statistical comparisons are between the entries in a column.

*Difference significant ($p < .005$) on Wilcoxon test.

†Difference not significant on Wilcoxon test.

Table 2
Reported Appearance of Illusory Brightness Difference

	Enhanced	Diminished	Same
Dots stereoscopically in front	34	6	20
Dots stereoscopically behind	9†	47*	4*

Note—The entered numbers are the totals of each of the three permitted judgments, pooled for all "in front of triangle" and all "behind triangle" displacements of the dots. Statistical comparisons are between the entries in a column.

*Difference significant ($p < .005$) on Wilcoxon test.

†Difference significant ($p < .02$) on Wilcoxon test.

"diminished" judgments were made when the dots were perceived as on the same plane as the broken triangle. Of the 24 judgments of the brightness difference made when the stimulus figure was entirely on the same plane, 17 were that the effect was the same in both displays. Five of the 7 judgments that the effect was enhanced in the stimulus display were made when the S judged that the dots were in front of the triangle.

The majority of judgments made when the two parts of the stimulus figure were on the same plane was therefore as expected. It is interesting that most of the "enhanced" judgments in this condition occurred when the dots in the stereo display were perceived as in front of the triangle, though they were in fact presented at the same distance.

In the conditions in which the dots and the broken triangle were presented at different distances, the direction of the distance difference was always perceived correctly. The histograms show a marked trend for the illusory effects to be enhanced when the dots were perceived as lying in front of the broken triangle, and diminished when perceived as lying behind. This was tested statistically by pooling the judgments across the conditions where the dots and the triangle were presented at different distances. Table 1 shows the total numbers of judgments of how the illusory contours in the stimulus figure compared with those in the comparison figure. Twenty-two of the 48 judgments that the contours of the stereo test figure were weaker when the dots were behind were in fact statements that no contours could be perceived at all in this display.

A similar pooling was made for the judgments of brightness difference in the 10 conditions where there was an objective depth difference. The results of this are shown in Table 2. Twenty-eight of the 47 judgments of diminished brightness difference in the stereo test figure with the dots behind were statements that there was no brightness difference—that is, there was no illusory effect. If the scores for the "enhanced" and "same" judgments are combined, then the differences between the conditions where the dots were in front and those in which they were behind are highly significant, both for the contours and brightness difference ($p < .005$, Wilcoxon test). So when the dots are brought forward there is a strong tendency for the illusory figure to

Fig. 5. Three figures showing various displacements of the dots relative to the broken triangle (see text for details).

persist and be enhanced, and when behind the broken triangle, to be diminished or disappear.

We now consider what, on our explanation, could be artifacts of this situation. In the monocular views, the effect of increasing the distance between the two plates is to displace the three dots horizontally from the broken triangle. Figure 5a shows a monocular view of the largest displacement. It can be seen that the illusion still persists in this figure. It remains possible that contours produced by horizontal displacements are somewhat weaker; but if so, this could not explain our finding that the contours are stronger when in front than when behind the broken triangle—for the dot displacements remain unchanged when the Polaroids are switched to reverse depth.

Secondly, size constancy will produce a smaller apparent separation of the dots when in front of the triangle than when behind, although their physical separation, as given by the collimated light system, remains constant. Figures 5b and 5c show two versions of Fig. 3 in which this separation is physically increased and reduced, respectively. There appears to be no obvious difference in the strength of the illusion. We assume this to apply also to apparent separation.

Thirdly, it might be considered possible that the effect is produced by conflict between the two-dimensional cues (or flat appearance) of the screen and the distance of the dots as seen behind the screen. If this is the case, it must be a very subtle effect, since the screen is not noticeable while looking at the stereo display. Rather, the broken triangle and dots appear as in an illuminated tunnel delineated by the circular edge of the screen. There was no suggestion from the Ss' reports that they had any special difficulty in perceiving the dots behind the broken triangle, which was at the distance of the screen. However, a short experimental check was made to try to rule out this possibility. The following modifications were made to the stereo "test" apparatus, which was used in the main experiment. The translucent Perspex screen was replaced with a piece of the same material but with clearly visible scratches to increase any such conflict information. Ambient light was also added to make the situation as "bad" as possible. The dots and the broken triangle were reversed in depth, so that the dots were at the screen and the broken triangle at its maximum displacement (5 cm) behind the dots. Seven fresh Ss individually viewed this display with each orientation of the Polaroids. The

Polaroids were intermittently switched, giving reversing stereo depth, until the S was confident of his judgment of the relative strength of the illusion for each orientation. All Ss reported that the illusion was present when the broken triangle was seen behind the dots, and in every case their depth judgments were correct. Only one S reported any appearance of illusory contour when the triangle was in front of the dots, and this was apparently weak. She reported a "bending back" of the illusory triangle. This curious three-dimensional effect was also found in the main experiment and will be discussed below. The only effect which was not found during the main experiment was that when the triangle was presented in front of the dots, two Ss initially reported that they were at the same distance, though they later detected the relative distances. At no time did they report the illusion in that condition. Whatever the position of the clearly visible screen between the triangle and the dots, it does not seem to affect the phenomena. We therefore suppose that screen texture is not significant.

Two of the explanations for the illusory contours described earlier are not consistent with these results. Neither the Gestalt "closure" nor the "feature detector" paradigms suggest plausible hypotheses for such illusory contours generated in these conditions. Concave illusory figures (Gregory, 1972a, b) are counter to the Gestalt-type interpretation. The asymmetry for depth reported here—that the illusory contours virtually disappear when the dots are forced (by stereo disparity) behind the broken triangle but remain at full strength when in front of it—is not to be expected on what is known of feature detectors. It would be a surprising property of the striate detectors, as currently understood from physiological data. Since partial object masking must present an almost continual problem for perception (Gibson, 1950, p. 143; Hochberg, 1965, p. 34ff.), we suggest that its necessary cognitive strategies could be sufficiently powerful to postulate nonexistent objects, given data such as otherwise improbable gaps. Our hypothesis for these effects is thus in terms of object information rather than stimuli: for information may be given by *absence* of stimulation.

Another aspect of the results provides further evidence for the notion of a postulated masking object "explaining" the gaps in the broken line triangle. The histograms in Fig. 6 show how the number of "diminished" judgments increased as the distance at

Fig. 6. Bar histograms showing the distributions of each kind of judgment of the illusory contours and brightness differences in the stereo display, compared with the two-dimensional display. The number of obtained judgments (from a possible total of 12) is shown on the ordinates, while the distance between the two display plates (and hence the stereo displacement) is shown on the abscissae. The distributions above the horizontal bisecting line in each figure were obtained when the dots were presented in front of the broken triangle, those below it, when presented behind. (At zero distance between the two plates, the dots were presented on the same plane as the broken triangle, whether the Polaroids were oriented to yield "dots in front" or "dots behind.")

which the dots appeared behind the broken triangle was increased. Most of the "enhanced" or "same" judgments which appear to go against the "masking object" hypothesis were made when the dots were only 1 or 2 cm behind the broken triangle. It is interesting that when illusory contours were perceived in this situation, several Ss spontaneously reported that the illusory figure curved back in depth from the broken triangle, to join the dots at its corners. In this way, a *three-dimensional* illusory figure was produced. When the dots were presented at the same distance in front of the triangle, this illusory figure was never seen as curving forward. Such three-dimensional illusory figures are reasonable cognitive solutions to the masking problem presented, but are surely extremely unlikely to be due to "three-dimensional curved feature detectors," if only because this would imply the existence of a vast repertoire of feature detectors available for triggering by simple stimuli. We suggest that the three-dimensionally curved figure is seen only when the dots are accepted as perceptual data for a masking object which would have to be curved in depth to be in front of the gaps. The

curved contours are not perceived when the dots are at their further positions because this would require a highly improbable shape of masking object.

There is one feature of the results that is not immediately predictable from any of the proposed explanations. It can be seen from Fig. 6 that when the dots are perceived as in front of the broken triangle, the distance at which an "enhanced" response is most likely is 3 cm, the likelihood of this response falling off at greater or lesser depths. This trend was not statistically significant, but the suggestion of an "optimum distance" for the illusory effect may be worth examining in future research.

REFERENCES

- Coren, S. Subjective contours and apparent depth. *Psychological Review*, 1972, 79, 359-367.
- Gibson, J. J. *The perception of the visual world*. Boston: Houghton Mifflin, 1950.
- Gregory, R. L. Stereoscopic shadow images. *Nature*, London, 1964, 203, 1407-1408.
- Gregory, R. L. *The intelligent eye*. London: Weidenfeld & Nicolson, 1970a.

- Gregory, R. L. On how so little information controls so much behaviour. *Ergonomics*, 1970b, 13, 25-35.
- Gregory, R. L. Techniques and apparatus for the study of visual perception. *Scientific Progress*, Oxford, 1970c, 58, 359-378.
- Gregory, R. L. Cognitive contours. *Nature*, London, 1972a, 238, 51-52.
- Gregory, R. L. A look at biological and machine perception. In B. Meltzer and D. Michie (Eds.), *Machine intelligence 7*. Edinburgh: Edinburgh University Press, 1972b.
- Gregory, R. L. The confounded eye. In R. L. Gregory and E. H. Gombrich (Eds.), *Illusion in nature and art*. London: Duckworth, 1973.
- Hochberg, J. E. *Perception*. Englewood Cliffs, N.J.: Prentice-Hall, 1965.
- Hubel, D. H., & Wiesel, T. N. Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. *Journal of Physiology*, 1962, 160, 106-154.
- Kanizsa, G. Margini quasi-percettivi in campi con stimolazioni Omogonea. *Rivista di psicologia*, 1955, 49, 7-30.
- Lawson, R. B., & Gulick, W. L. Stereopsis and anomalous contour. *Vision Research*, 1967, 7, 271-297.
- Lee, D. N. Theory of the stereoscopic shadow-caster, an instrument for the study of binocular kinetic space perception. *Vision Research*, 1969, 9, 145-156.
- Pastore, N. *Selective history of theories of visual perception, 1650-1950*. Oxford: Oxford University Press, 1971.
- Schumann, F. Einige Beobachtungen über die Zusammenfassung von Gesichtseindrücken zu Einheiten. *Psychologische Studien*, 1904, 1, 1-32. (Cited in R. S. Woodworth. *Experimental Psychology*. New York: Holt, 1938.)

(Received for publication July 6, 1973;
revision received November 12, 1973.)