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Perception of Partly Occluded Objects and Illusory Figures: Evidence for an Identity Hypothesis

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Three experiments test the hypothesis that perception of partly occluded figures (POFs) and illusory figures (IFs) derive from a single visual interpolation process. In each, 2 magnitude estimation tasks were used. One assessed perceived unity of visible parts of POFs; the other perceived clarity of edges in IF displays. Exps. 1 and 2 tested the effects of relative positions and orientations of edges on perceived unity and clarity. Exp. 3 used randomly generated displays to test whether edge relations sampled at random would exert the same effects on POFs and IFs. All studies showed nearly perfect correlations between perceived unity and perceived edge clarity, when the physically specified parts of the figures were identical. The specific conditions under which edges are interpolated fit well with predictions of a recent theory (Kellman & Shipley, 1991). These results suggest that a single unit-formation process underlies "modal" and "amodal" completion.

Perceptual representations are said to go "beyond the information given" when some of their contents have no local stimulus determinants. Ordinary object perception is a conspicuous example. Although most viewed objects are partly occluded by others, their boundaries are for the most part accurately perceived.

Michotte, Thines, and Crabbe (1964) termed this ability *perceptual completion* and distinguished two types. *Modal* refers to the presence of sensory attributes; "subjects do not differentiate between parts which have been added and those which have a physical correlate. These additions have the same visible attributes or 'modes' (brightness and hue) as the rest of the figure, hence the term 'modal'." The perception of parts of objects without local sensory attributes (e.g., as a result of occlusion) was designated *amodal completion.* According to Michotte et al.:

> The word 'amodal' is used here with a primarily negative meaning; it is intended to imply that the completed portion wholly lacks visible attributes. Nonetheless, the completion is perceived; it is neither an inference nor a projection of some mental image, but a direct perception.

Perception of the unity and boundaries of partly occluded objects is an example of amodal completion that is pervasive in ordinary perception. The examples of modal completion given by Michotte et al. are more obscure. However, the phenomenon of illusory figures provides a well-known example. Contours and figures are perceived across homogeneous regions of displays as illustrated in Figure 1. Although there is physically no local boundary where the illusory edges are seen, the perceived edges have sensory characteristics.

Most treatments of these phenomena have implicitly or explicitly followed Michotte et al.'s (1964) suggestion that there are two processes of completion: modal and amodal. From a sensation-based view of perception (see discussion by Hochberg, 1974), amodal and modal completion must not only be separate processes but must differ radically in character. Illusory figures, because they have local sensory attributes, are clearly perceptual phenomena. Knowledge of partly occluded areas, however, would have to be classified as a cognitive rather than perceptual phenomenon because there are no sensory accompaniments. The restriction of perceiving to phenomena accompanied by local sensations is not shared by those who view perception as more abstract and its relation to sensations as more incidental (Gibson, 1979; Kanizsa, 1979; Michotte, 1963; Michotte et al., 1964).

In this article, we suggest that amodal and modal completion are not different perceptual processes. Edges perceived without local information in both cases derive from a single unit-formation process (Kellman & Loukides, 1987; Kellman & Shipley, 1991; cf. Kanizsa, 1979). Whether these edges take on an amodal or a modal appearance depends on factors outside the unit-formation process. Specifically, the different phenomenal appearance of interpolated edges arises from the depth relations between units formed and other surfaces and not from differences in the process of unit formation. Elsewhere we proposed a detailed theory of the stimulus variables that control unit formation (Kellman & Shipley, 1991). Some aspects of this theory are introduced later in connection with the present experiments. The main focus of the present work, however, is to test experimentally the underlying premise of a single unit-formation process.

Although experimental data must be central in assessing

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this idea, there are other arguments, based more on logic and parsimony, that support it. We review here the arguments presented by Kellman and Loukides (1987) and Kellman and Shipley (1991).

One argument comes from the observation that illusory figure displays sometimes exhibit bistability (e.g., Bradley & Petry, 1977). Consider the display in Figure 1c. It may appear as a filmy, partly transparent, illusory figure on top of four gray figures. With continued viewing, however, one may notice a different appearance: a partly occluded figure seen through four holes in the white surface (in front of a more distant gray surface also seen through the holes). When this shift occurs, the display has changed from an example of modal completion (illusory figure appearance) to amodal completion (partly occluded figure). From a sensation-based perspective, the figure is given perceptually in the former case but cognitively in the latter. It is noteworthy that the shape of the interpolated boundaries (i.e., those not physically specified) is the same in the two appearances. The perceived figure has the same boundaries whether it appears through holes in the surface or in front of gray figures.

A second important phenomenon is *spontaneously splitting figures* (Koffka, 1935; Petter, 1956). Figure 2 gives an example. The black area is physically homogeneous yet may be seen as having boundaries within it. This phenomenon has been said to illustrate simplicity principles in perception (Arnheim, 1974; Kanizsa, 1979; Koffka, 1935). Another interesting feature of spontaneously splitting figures is that they may be ambiguous as to which unit lies in front of the other (i.e., which one is modally and which one is amodally completed). The unit seen as nearer than the other will be modally completed (i.e., it will have illusory contours as boundaries). The other unit will be amodally completed (i.e., it is a partly occluded object). In ambiguous displays, both the position—and amodal or modal character—of each unit reverses together. This shift in depth arrangement also characterizes the bistable transparency–partial occlusion display discussed previously here.

It is possible to think of modal and amodal completion as separate processes that just happen to appear in complemen-

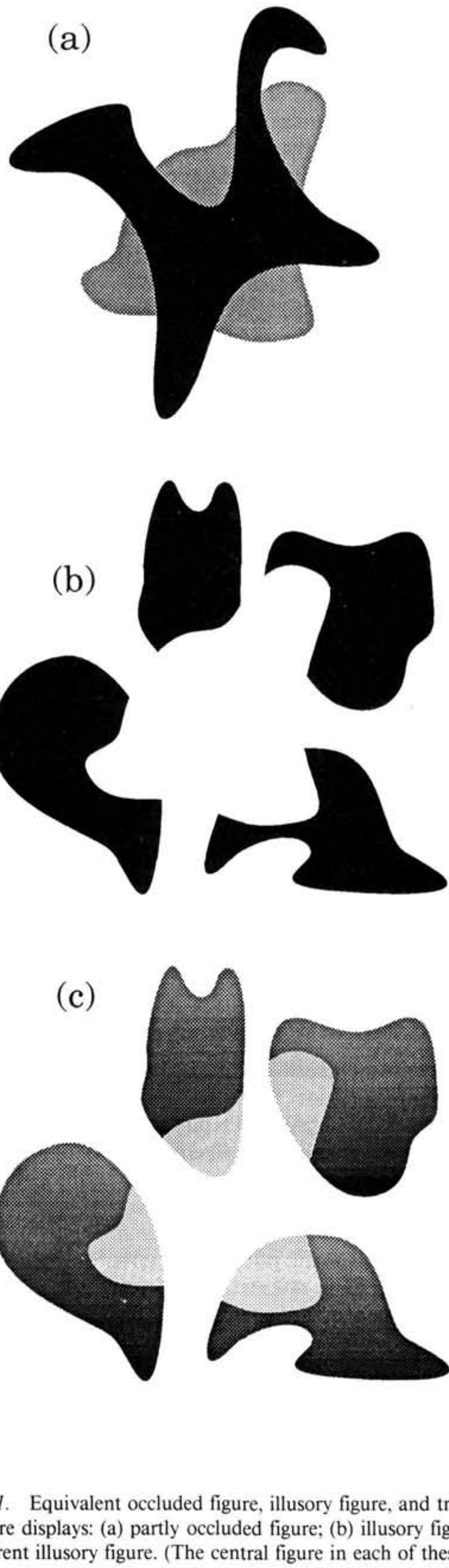

Figure 1. Equivalent occluded figure, illusory figure, and transparent figure displays: (a) partly occluded figure; (b) illusory figure; (c) transparent illusory figure. (The central figure in each of these three cases has the same edges specified by luminance differences, and the interpolated edges appear to be the same in each case.)

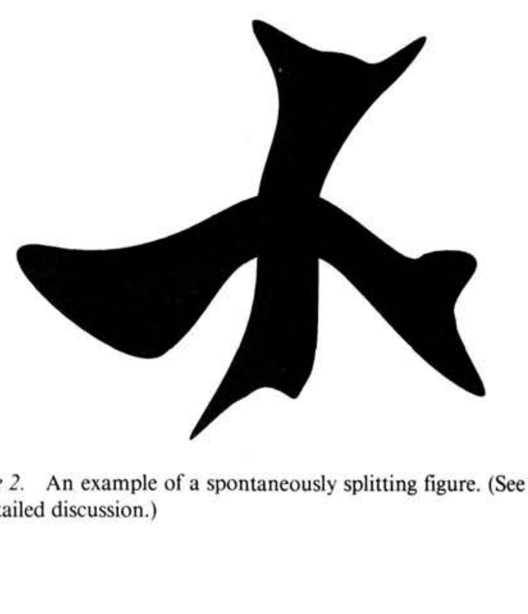

Figure 2. An example of a spontaneously splitting figure. (See text for detailed discussion.)

tary or competing manner. A simpler hypothesis, however, is that a single unit-formation process is at work in the modal and amodal versions of each display. When reversals occur, it is not unit formation that changes but only the depth relations between units formed and other surfaces in the array. The interpolated boundaries in the perceived objects or figures remain the same; their appearance as modal or amodal merely depends on whether another surface is assigned a nearer position in depth. Bistability in depth arrangement occurs when there is little or no depth information indicating the depth order of some adjacent surfaces. (An interesting constraint seems to apply such that units whose projections overlap must be assigned a depth order even if it is arbitrary and shifts over time.)

On this hypothesis, modal and amodal completion do not name two different completion processes. There is only one interpolation process: Whether its products appear to be nearer than or behind other surfaces determines the phenomenal difference denoted by modal and amodal. We refer to the hypothesis of a single interpolation process as the *identity hypothesis*.

Equivalence Criteria

The figures whose shape and interpolated edges remain the same despite the shift from amodal to modal also retain the same physically specified parts of their boundaries. Interpolation occurs between these physically specified edges. This suggests a natural notion of formal equivalence of occluded and illusory figure displays. For every occluded display, one can construct an illusory figure display in which the same portions of the figure are specified physically and vice versa. The central question of the present work is: Given equivalent arrangements of physically specified edges, will interpolation work the same way in occluded object and illusory figure contexts? If the amodal–modal difference is merely a difference in ultimate appearance as a result of depth placement of units rather than a difference in unit-formation process, then interpolation should work in the same way in equivalent occluded and illusory figure displays.

To test such a hypothesis, some additional comments are needed about the criteria and transformation rules used to generate equivalent occlusion and illusory figure displays. Obviously, equivalent occluded and illusory figure displays will differ in ways that are pertinent to the differing depth organization of these two types of displays. Their equivalence consists, however, in their having the same physically specified edges relevant to the unit-formation process; their differences lie elsewhere. Determining exactly which edges are and are not relevant, however, is not a conceptually simple matter. In practice, however, it is possible to make the differences between display types rather remote from the relevant loci of interpolation and irrelevant from almost any theoretical perspective.

Three other issues require comment. First, the relevant edges must be the edges of extended regions rather than very thin lines (Kanizsa, 1979). (Outlines are not equivalent to the edges of surfaces in the unit-formation process; for a discussion see Kellman & Shipley, 1991.) Second, the edges relevant to the interpolation process are those that lead into first-order discontinuities (i.e., sharp corners) in the boundaries of projected regions (Kellman & Loukides, 1987; Kellman & Shipley, 1991; Shipley & Kellman, 1990).[1] Edges that do not lead into a sharp corner at any point (such as the boundary of a circle) do not initiate edge interpolation. The presence of discontinuities is unavoidable in occlusion cases because any occlusion introduces projected discontinuities at the point of occlusion (for a proof, see Kellman & Shipley, 1991, Appendix A). The relevant design consideration, then, applies to illusory figure-inducing elements. These must possess first-order discontinuities (Shipley & Kellman, 1990). In all of the displays used later, these discontinuities occur in the same locations as those in the equivalent occlusion displays.

A projected first-order discontinuity (sharp corner) ordinarily has two edges leading into it. Our equivalent illusory figure and occlusion displays in general equate both of these edges even though it is often clear that one is more important to the interpolated boundaries in a particular case. Thus, the curved edges in the occluding figure in Figure 1 match the curved edges of the illusory figure-inducing elements in the neighborhood of the central figure. In addition, it is important to avoid cases in which extraneous surface edges that differ between illusory figure and occlusion displays might affect the unit-formation process differently.

In Figure 1, the physically specified edges around the central area of the display are the same. In Figure 1a, these edges are the boundaries of the visible parts of a partly occluded figure. The relevant edges are given by differences between the surface luminance of the visible parts and the white background. In Figure 1b, the same edges are given by what are usually referred to as illusory figure-inducing elements. Now the background color is on the inside of these boundaries. In Figure 1c, an apparent transparency display, the physically specified edges of the central figure are given by the boundary between the lighter and darker gray regions.

Transformation Rules

In general, the transformation of a partially occluded figure display into an illusory figure display involves the creation of a set of inducing elements with one inducing element for each visible part of the occluded figure. The visible edges of the partially occluded figure form the part of the boundary of each inducing element that defines the central figure (target figure edges). The exact shape of the remaining boundary of each inducing element (nontarget edge) is constrained by two requirements. First, discontinuities in the first derivative of the luminance-specified edges are required. Second, the nontarget boundaries should not interfere with the unit-formation process acting on the target edges. Two strategies for forming

[1] Discussion of the determination of physically specified boundaries is beyond our scope here. In the present work, such edges will always be given by clear luminance discontinuities. Boundaries so defined are characteristic of occlusion boundaries in ordinary viewing and are readily detectable by plausible edge-finding algorithms (Watt, 1988). Whether other luminance profiles can also serve as inputs to the unit-formation process has not been fully investigated.

nontarget edges that usually satisfy both requirements involve constraining the orientation of the nontarget contours adjacent to the target edges. The nontarget edges could either be placed where the occluder's edges had been or they could be perpendicular to the target edge. Figure 1b illustrates an illusory figure display generated from the occluded figure in Figure 1a using the first rule, and Figure 9b illustrates illusory figures generated by applying the second rule to displays in Figure 9a. Each strategy has its advantages. Using the first strategy will tend to limit interference from nontarget edges on target interpolation because the nontarget edges will be aligned with other nontarget edges. Alternatively, the second strategy is guaranteed to produce robust discontinuities.

The creation of a partially occluded figure from an illusory figure display is simply the reverse transformation. The physically specified edges that define the illusory figure form the edges of the visible parts of the occluded object. In this case, the shape of the occluder is underdetermined. The rules for determining the shape of the occluder are similar to those for the nontarget edges of the inducing elements. The occluder should be constructed so that its edges do not interfere with unit formation. It should be smooth at each of the points where the target edges of the occluded figure intersect the occluder. The shape of the occluder may be further constrained by limiting the orientation of its edges at each of the points where the target edges of the occluded figure and occluder meet. The occluder may be either perpendicular to the target edges or tangent to the nontarget edges of the inducing element.

From the mechanics of transforming occluded and illusory figure displays, we can gain some insight into the reason a figure appears as one or the other. Differences in the modality of the interpolated figure in the two cases result from pictorial depth information. Specifically, for occluded figures at the relevant points of discontinuity, the physically specified edges of the occluder continue through the discontinuity. A specified edge continuing through a discontinuity is one way of describing the depth cue of interposition. Any interpolated edges must be behind the physically specified edge. The situation is quite different with illusory figures; at the relevant points of discontinuity neither edge continues. Thus, the edge of the interpolated central figure in Figure 1b can appear unobstructed. For further discussion of the relation between interpolation and interposition, see Kellman and Shipley (1991).

Testing the Identity Hypothesis

Given the foregoing considerations of display generation, the present experiments involve manipulations of the positions and relations of physically specified edges to determine whether or not they have comparable effects on unit formation in occlusion and illusory figure cases.

It is worth noting at the outset some complexities inherent in the idea of a single process underlying phenomenally different appearances (i.e., illusory vs. partly occluded figures). The differing appearances in the two cases are perceptually obvious and could in principle affect certain sorts of responses. The completed figure whose boundaries are interpolated under occlusion is seen as having some parts out of sight, hidden behind an occluding surface, whereas an illusory figure is not. Even if a single process is at work, it would not be surprising if in some tasks responses to illusory figures differed from those for occluded figures by a constant factor. If a certain variable had substantially differing effects on occluded and illusory figures, however, it would provide evidence against the identity hypothesis.

Experiment 1

If unit formation in both occluded and illusory figures is based on a common process, then variables that affect the process should have an equivalent effect in the two classes of displays. In our first test of this hypothesis, subjects performed two magnitude-estimation tasks.[2] Following Dumais and Bradley (1976), subjects assigned numbers to the clarity of perceived edges in illusory figure displays on a scale from 1 to 10; a robust example of an illusory figure was used as a modulus (a Kanizsa triangle display was assigned a rating of 10). Following Kellman and Spelke (1983), subjects rated the apparent connectedness of visible parts in occlusion displays using a 10-point scale (a robust example of perceived unity despite occlusion was assigned a value of 10). Sets of illusory figures and partially occluded figures were matched by constructing one set and then applying the rules for transforming that type of display into the other. As a result, for any given display in one set there was a display in the other set such that the specified (luminance-defined) regions of the potential illusory or partially occluded figure were identical.

For this initial test of the identity hypothesis, we used pairs of edges with the same orientation and varied their misalignment. Virtually all accounts of amodal and modal completion recognize that collinear edges support unit formation. This relation is included in the Gestalt notion of good continuation (Wertheimer, 1912) as well as in Gestalt-oriented accounts of amodal completion (Kanizsa, 1979; Michotte et al., 1964) and illusory figures (Kanizsa, 1979) and other approaches (Grossberg & Mingolla, 1985). According to our recent theory (Kellman & Shipley, 1991), the tolerance of the interpolation process for misalignment of parallel edges should be confined to a narrow threshold around collinearity. Varying misalignment was thus considered valuable for checking this hypothesis as well as determining this threshold.

Method

Subjects. Twenty-four undergraduates at Swarthmore College served as subjects in 45-min individual testing sessions. Each subject received $3 for participating.

Apparatus. All stimuli were designed and presented on a Commodore Amiga computer with a Commodore 1080 RGB monitor (20 × 25 cm). The screen's resolution was 400 × 640 pixels.

Subjects were positioned 150 cm from the monitor. The only source of light in the room other than the monitor was a screened

[2] A brief summary of this experiment was presented in Kellman and Shipley (1991).

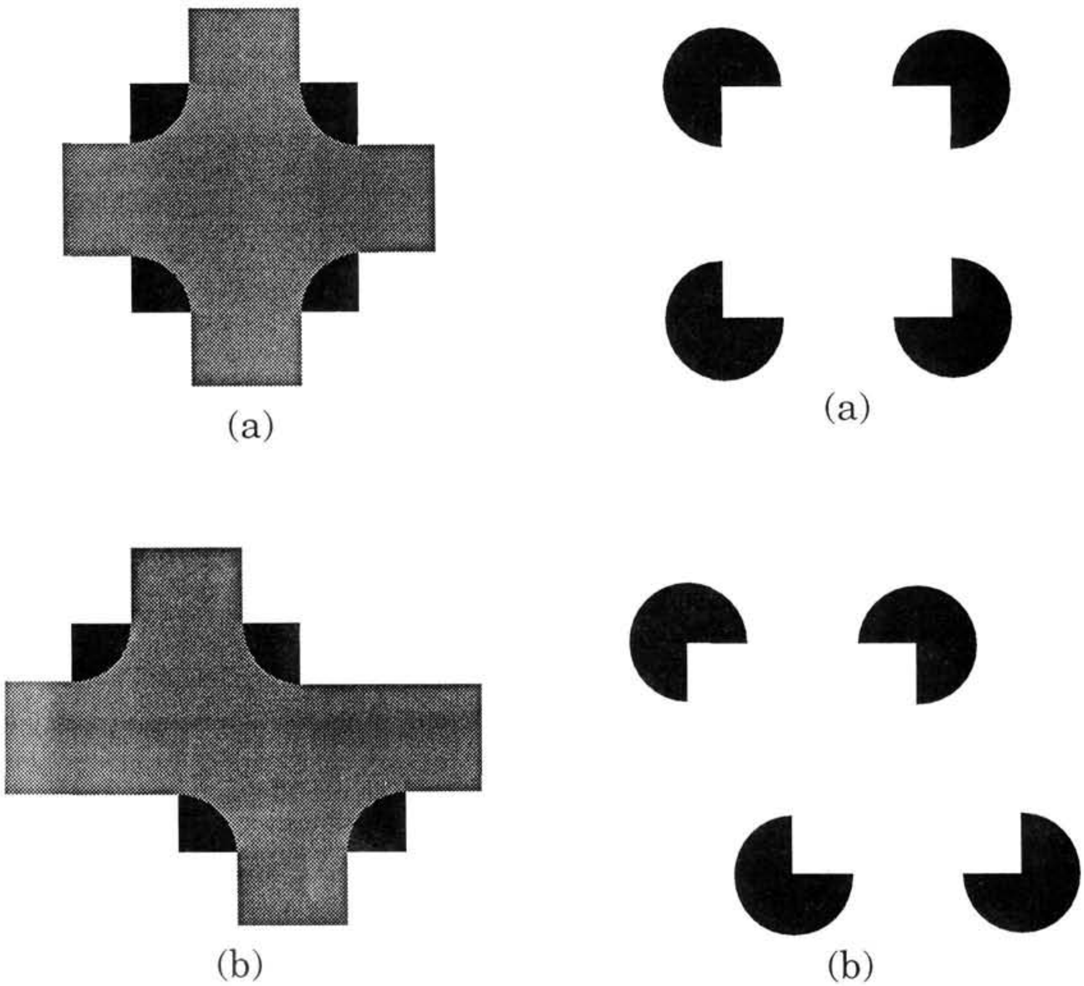

Figure 3. Examples of displays used in Experiment 1: (a) partially occluded figure displays with no edge misalignment and the corresponding illusory figure display; (b) partially occluded figure display and the corresponding illusory figure display with misaligned edges. (*Note.* From "A Theory of Visual Interpolation in Object Perception" by P. J. Kellman and T. F. Shipley, 1991, *Cognitive Psychology, 23,* p. 164. Copyright 1991 by Academic Press. Reprinted by permission.)

100-W bulb positioned above and behind the monitor. This lighting arrangement reduced reflections from the monitor.

Stimuli. Equivalent sets of illusory figures and occluded figures were used. Equivalence between the two sets of displays was achieved by constructing one set of displays so that each display matched a display in the other set in size and position of the luminance-defined edges of the unit of interest (illusory figure or partially occluded figure). Examples of two displays from each set are shown in Figure 3. Each set contained 23 displays in which the alignment of the edges of the potential unit varied. In the illusory figure displays, alignment was varied by displacing two of the adjacent inducing elements from an illusory square display. Displacements in the occlusion displays were achieved by displacing two of the visible areas of the occluded square. Besides one display with no misalignment of edges, 11 vertical and 11 horizontal displacements were used. Vertical misalignments included all those from 1.75 to 15.81 min of visual angle by 1.75-min increments as well as values of 26.33 and 35.12 min. Horizontal misalignments included all those from 1.49 to 13.42 min by 1.49-min increments as well as values of 22.38 and 29.83 min. The 22 displacement displays along with a no-displacement display formed each set of 23 displays.

Procedure. All subjects were shown both the illusory figure displays and partially occluded figure displays. Half of the subjects performed the occluded figure task first, and half did the illusory figure task first. Subjects were instructed only for the first task at the beginning; instructions for the second task followed completion of the first. All displays within a set were presented to each subject in random order with the constraint that for any given subject who received a particular random order there was another subject who was presented with the stimuli in the reverse order.

For the partially occluded figures set, subjects were given the following instructions:

> [A white ellipse occluding the center of a red rectangle was shown to the subject.] In this part of the experiment, you will see a number of displays like this display. We would like you to decide if all the colored sections appear to be parts of a single figure, and rate the strength of this impression on a scale from 0 to 10.

> A rating of 10 indicates that all the colored areas clearly appear to be part of a single figure, and 0 indicates that they do not appear to be the parts of one single figure. For example, in this display the colored areas clearly appear to be a single figure: a rectangle. This would be given a 10.
>
> [A white rectangle occluding two separate circles was then shown.] The colored areas in this display do not appear to be parts of a single figure. This would be given a 0. Do you have any questions so far?

The following instructions were used to introduce the task for the illusory figure set.

> [A Kanizsa triangle illusory figure display with white inducing elements on a black background was shown to the subject.] This is an example of an illusory figure. Most people report seeing a black triangle in the center of this display. In this experiment you will see a number of displays like this display; we will be asking you to judge the clarity of the illusory contours, that is, the edge between the white areas. [The experimenter indicated this area with a pointer.] Use a scale from 0 to 10, where 10 means you see a sharp clear illusory edge, as in this display, and 0 means you see no illusory edge. [The subject was then shown a display in which small white dots delineated the corners of a triangle identical in size to the triangle in the first display.] In this display, one does not see an illusory figure. Although one could imagine a central triangle, there are no clear edges between the white areas, so this would be rated a zero.
>
> [An illusory rectangle with three-quarter circle white inducing elements was shown.] This is another example of an illusory figure with fairly clear edges between the white areas. [A display was then shown that was similar to the previous one except the inducing elements were line drawings. Such outlined inducing-element displays do not produce illusory figures; Kanizsa, 1979.] This is an example in which there is no clear illusory figure; it should be given a low rating on the scale. Do you have any questions so far?

After the instructions in each case, subjects were then shown the sequence of displays and gave magnitude estimations for each.

Results

Preliminary analysis showed no differences between horizontal and vertical misalignments within each display set (occluded figures or illusory figures). Pairwise comparisons were performed for each pair of horizontal and vertical misalignments that differed by less than 0.5 min of visual angle. There were four such pairs within each set (1.75° horizontal and 1.49° vertical; 7.02° and 7.46°; 8.78° and 8.95°; 10.54° and 10.44°). The t^* values for all eight comparisons were less than 1.2. Given the isotropy of alignment effects, results of the vertical and horizontal misalignments have been combined for purposes of further analysis.

Figure 4 presents the mean unity ratings for occluded figures and mean edge clarity ratings for illusory figures for the 23 displays as a function of misalignment in visual angle. The effect of alignment in the two types of displays was virtually identical. For both, strength of interpolation of edges seems to drop off rapidly with misalignment of edges up to about 15 min of arc. The correlation between mean illusory edge clarity ratings and mean partially occluded figure unity ratings was .981 ($p < .01$). Furthermore, each subject showed considerable similarity in the effect of alignment on his or her ratings. The mean individual correlations between illusory edge clarity and unity was .821, with a range of .541 to .906.

Subjects' initial ratings were also analyzed. Using the first five ratings from the first set for each subject, the correlation between illusory figure clarity and partially occluded figure coherence was .952 ($p < .01$).

Discussion

The effect of misalignment of edges on unit formation appears to be identical in illusory figures and partially occluded figures. The clarity of edges in an illusory figure display predicts almost perfectly the perceived unity of the visible parts of an equivalent partially occluded figure and vice versa. This result is consistent with a model of unit formation in which the process responsible for the perception of illusory contours and partially occluded figures is the same. The experiment also provided some specific information about the unit-formation process: Interpolation between parallel edges requires them to be aligned or nearly so. Strength of unit formation dropped rapidly with misalignment. Interpolation appears weak or nonexistent beyond about 15 min of arc misalignment. As noted elsewhere (Kellman & Shipley, 1991), this value is well above thresholds for human adult vernier acuity but is on the same order of magnitude as misperceptions of alignment in the Poggendorf illusion (Robinson, 1972).

There is at least one alternative explanation for the main finding of Experiment 1—the nearly perfect correlation of edge clarity and unity ratings. Perhaps subjects did not base their responses on their percepts and instead based them on the degree of misalignment. After seeing several displays, subjects may have noticed that alignment was being varied across displays and used this to guide their responses. Analysis

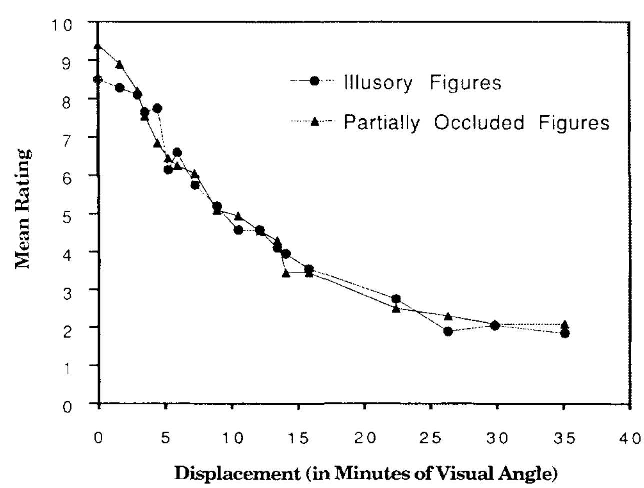

Figure 4. Mean ratings of partially occluded figure unity and illusory contour clarity as a function of edge misalignment ($n = 20$). (*Note.* From "A Theory of Visual Interpolation in Object Perception" by P. J. Kellman and T. F. Shipley, 1991, *Cognitive Psychology, 23*, p. 166. Copyright 1991 by Academic Press. Reprinted by permission.)

of each subject's first five ratings in the experiment was performed to check this possibility. Presumably a subject would require more than a few displays to deduce that alignment was the primary variable in the displays. The correlation between subjects' ratings on the first five trials in the illusory figure task and the initial ratings of other subjects in the occluded figure task was very high. That this correlation differed little from the overall correlation in the experiment suggests that the alternative hypothesis does not explain the findings of Experiment 1.

Experiment 2

Whereas Experiment 1 studied the relationship between unit formation in illusory figures and partially occluded figures using a single variable (alignment of parallel edges), Experiment 2 investigated the effects and interactions of several variables. Specifically we manipulated position, orientation, and separation of the physically specified edges. These were selected to test the identity hypothesis over a range of conditions as well as to test aspects of a particular model of interpolation.

Kellman and Shipley (1991) proposed formal criteria of relatability (i.e., which relations between edges can support interpolation). In their model, two edges are relatable if their linear extensions meet in the extended regions. More formally, if r and R are perpendiculars drawn to the ends of two edges (see Figure 5a), with R assigned to whichever perpendicular is longer, and ϕ is the angle between R and r, then the two edges are relatable if $0 \leq R \cos \phi \leq r$ (see Kellman and Shipley, 1991). Thus, the limit of relatability is reached when $R \cos \phi = r$ as would occur if the linear extrapolation of E_2 meets the end of E_1. The other limit occurs when $R \cos \phi = 0$ as would occur if E_1 and E_2 were parallel.

The relatability criteria predict a particular kind of interaction between orientation and vertical position in interpolation. To illustrate this interaction, Figure 5b and 5c shows edges of identical orientations. In these two figures, the end of the top edge is the same distance from the bottom edge. In Figure 5b, it is displaced to the right and in Figure 5c to the left. Only in Figure 5b are the two edges relatable. (In Figure 5c, the linear extension of the bottom edge would intersect the top edge itself rather than intersecting it in its extended region.)

Using variations in both horizontal and vertical position and orientation of edges, Experiment 2 was thus designed to provide some preliminary data on this prediction as well as to test the identity hypothesis.

Method

Subjects. Twenty undergraduates at Swarthmore College served as subjects in 45-min individual testing sessions. Each subject received $3 for participating.

Apparatus and procedure. The procedure for Experiment 2 differed from that of Experiment 1 in that after all of the displays from one set were shown, 10 of the displays from that set were repeated. The same 10 displays were repeated for all subjects, and the equivalent illusory figure and partially occluded figure displays were used as the

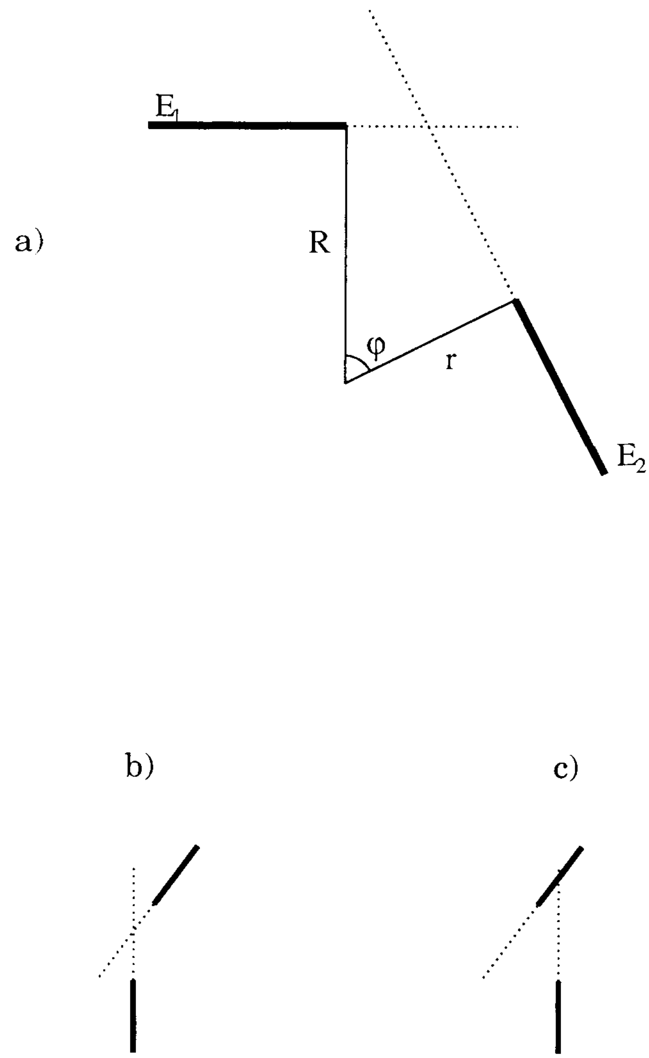

Figure 5. Illustration of the relatability criteria of Kellman and Shipley (1991): (a) E_1 and E_2 are surface edges (R and r are perpendiculars to E_1 and E_2 and ϕ is the angle between R and r); (b) relatable edges; (c) nonrelatable edges. (See text for detailed discussion.)

repeat displays in the respective sets. No break in the presentation sequence marked the transition between the original set and the repeat set. Responses to the repeated stimuli were used to measure the reliability of subjects' ratings.

Stimuli. Two sets of equivalent illusory figures and partially occluded figures were constructed for this experiment. As in Experiment 1, the size and position of the luminance-defined edges of the illusory figures and partially occluded figures were equated across the two sets. Like the displays used in Experiment 1, the illusory figure displays consisted of four inducing elements, and the partially occluded figure displays consisted of an occluder and four corners of a potential occluded figure. Rather than varying alignment of parallel edges, however, the displays in Experiment 2 varied in the alignment of edges with different orientations. To achieve varying degrees of alignment of nonparallel edges, displays were constructed by varying the placement of the right pair of edges (the two inducing elements on the right side in the illusory figure displays and the parts on the right side in the partially occluded figure displays), varying the orientation of these edges and varying the horizontal distance between the left and right edges. Five different vertical positions, three different edge orientations, and two different horizontal distances were used for a total of 30 displays in each set. Figure 6 shows six displays illustrating each level of the three factors. The five vertical positions were −0.37°, 0°, 0.17°, 0.33°, and 0.65° arc of displacement of the right edges from a position where all edges were at the same height. The three orientations of the right edges were 0° (horizontal), 13.5°, and 25.7°. The two horizontal separations among pairs of edges were 0.76° and 1.15° arc.

Results

Unity ratings for occlusion displays and illusory figure clarity ratings for the 30 displays in each set were closely matched as can be seen in Figure 7. The correlation between the mean clarity and unity ratings was .959 ($p < .01$). The mean individual correlation between clarity and unity ratings was .661 (range = .304–.910). These correlations were virtually the same as those between the first and second ratings of identical displays. The correlation between the mean ratings for the first and second presentations of illusory contours was .977 ($p < .01$) and for the partially occluded figure, .990 ($p < .01$). The mean individual ratings for illusory contours was .776 (range = .308–.981) and for partially occluded figures, .794 (range = .035–.989). Although these correlations are slightly higher than the overall correlations between illusory figures and partially occluded figures, this difference disappears when the illusory figures–partially occluded figures correlation is restricted to only the 10 repeated figures. The correlation between the illusory figures and partially occluded figures for the first presentation of these 10 figures was .972 ($p < .01$) and for the second presentation, .987 ($p < .01$).

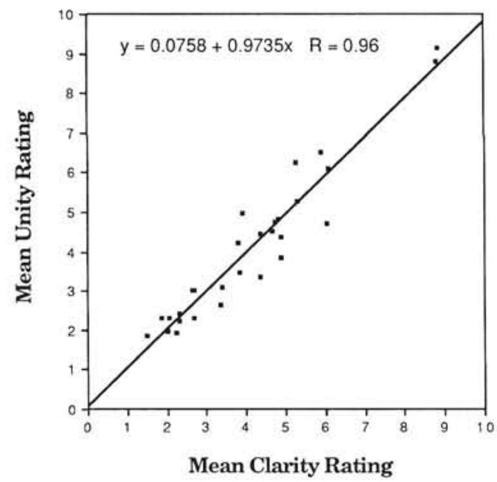

Figure 7. Mean unity ratings plotted against the corresponding illusory figure clarity ratings for Experiment 2 ($n = 20$).

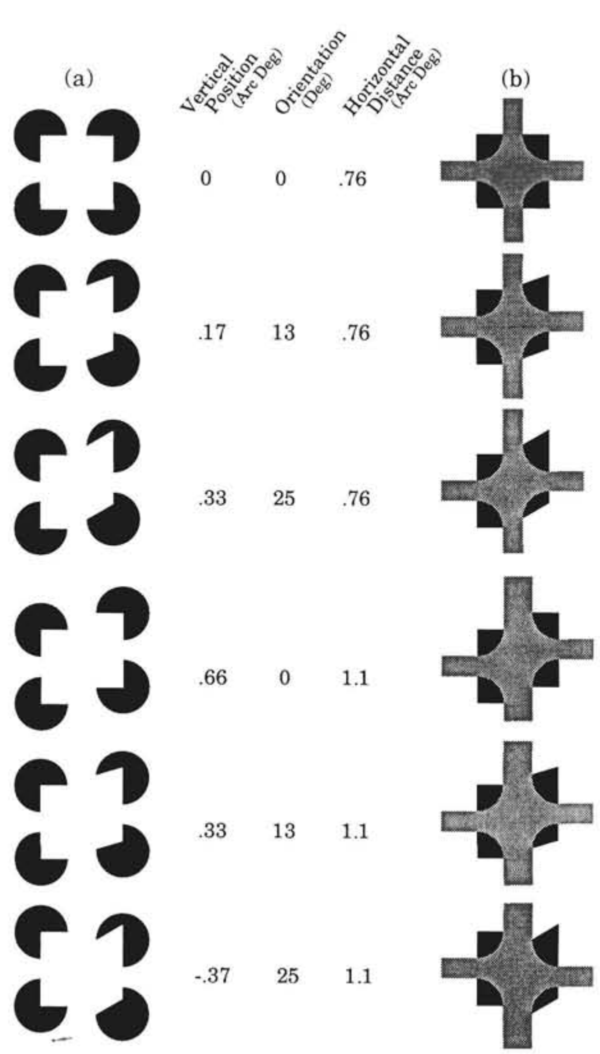

Figure 6. Examples of (a) the partially occluded figure displays and (b) the corresponding illusory figure displays used in Experiment 2. (See text for detailed discussion.)

To examine further the concordance of ratings across the two types of displays and to assess the effects of vertical position, orientation, and horizontal distance, the data were subjected to a four-way repeated measures analysis of variance (ANOVA), with vertical position of edge, relative orientation of edges, horizontal distance between edges, and type of display (illusory contour or partially occluded figure) as factors. The analysis in general confirmed the lack of difference in ratings of the two types of displays. There was no main effect of display type ($F < 1$). With one exception, there were no interactions between display type (occluded vs. illusory figure) and the other variables (all Fs < 1). The exception was the Display Type × Vertical Position × Orientation interaction, $F(8, 152) = 3.19$, $p < .003$. The reason for this interaction was not clear. Inspection of the individual displays showed that equivalent occluded figure and illusory figure displays never received ratings that differed by more than 1.3 rating points. However, three displays (of 30) had differences between 1 and 1.3 rating points, which was more than most others. (Most differences between unity and edge clarity ratings were within 0–0.4 rating points.) Because the three displays with wider disparities seemed to have nothing in common and because the disparities amounted to not much more than one rating point, we do not consider this result further.

Vertical position and orientation both affected the strength of interpolation. The ANOVA revealed a large main effect of vertical position, $F(4, 76) = 73.69$, $p < .0001$; interpolation was best when the top edges were in the region of relatability where their extrapolations would meet. For example, when the right edge was oriented at 13° to the left edge and displaced 0.33° upward, its rating was 4.6, whereas when displaced 0.37° downward it was 1.9. There was also a main effect of orientation, $F(2, 38) = 6.24$, $p < .005$. Most important for the relatability hypothesis, the predicted interaction of orientation and vertical position was strongly confirmed, $F(8, 152) = 36.49$, $p < .0001$. For example, when the edges were parallel, the rating with no misalignment was 8.9, and with 0.33° misalignment was 3.0, whereas for the orientation difference of 25°, the ratings for the same positions were 3.8 and 4.7, respectively. There was no main effect of horizontal distance ($F < 1$), but there was a reliable Vertical Position × Horizontal Distance interaction, $F(4, 76) = 4.73$, $p < .002$, and a reliable Vertical Position × Orientation × Horizontal Distance interaction, $F(8, 152) = 3.91$, $p < .0003$. Like the Vertical Position × Orientation interaction, these latter two interactions are consistent with the relatability criteria. In general, the closer two edges are to being parallel, the smaller the range of vertical displacement that should result in relatable edges. The Vertical Position × Horizontal Distance interaction may reflect the fact that for nonparallel edges the horizontal range of relatable positions will increase as the vertical separation between the two edges increases.

Figure 8 summarizes the data in terms of predictions made by the theory of Kellman and Shipley (1991). Ratings are shown for displays that were relatable, nonrelatable, and at the borderline for relatability ($R \cos \phi = r$). Although there is some overlap between categories, nonrelatable edges (mean rating = 2.4, $n = 28$) are generally rated well below relatable ones (mean rating = 5.4, $n = 32$, including those on the borderline of relatability).

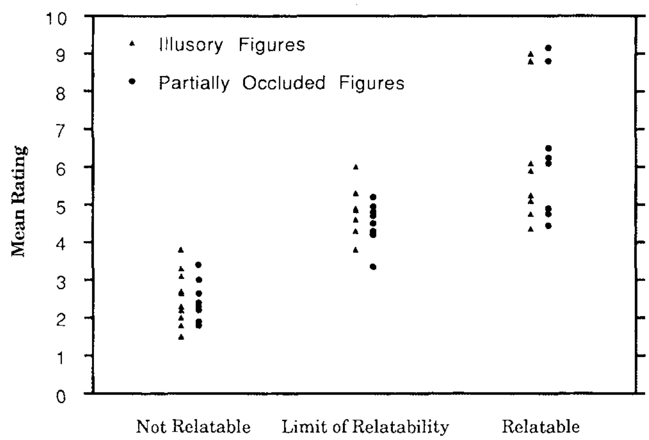

Figure 8. Mean ratings for partially occluded figure and illusory figure displays classified according to the relatability criteria. (See text for detailed discussion.)

Discussion

The results from Experiment 2 showed a strong concordance between ratings of unity under occlusion and illusory figure clarity. All of the variables tested—vertical position, orientation, and horizontal distance—exerted reliable effects on unit formation. These effects and their interactions were nearly identical across the occluded and illusory figure displays.

These results offer substantial support for a common mechanism of unit formation in illusory figures and partially occluded figures. The possible alternative explanation of the results of Experiment 1—that subjects might have adopted some strategy other than reporting their percepts—seems unlikely in Experiment 2 given the increased complexity of the display set.

Experiment 2 also provided results consistent with a particular hypothesis about which relations between edges support visual interpolation (Kellman & Shipley, 1991). The predicted interaction of vertical position and orientation was one of the strongest effects in the data. Specific assessment of relatable and nonrelatable edges showed a clear drop-off in ratings of interpolation for the latter, although there was some overlap between groups.

Some overlap is not surprising given that perceptual thresholds must necessarily be involved in the detection of relatability. Exactly what sort of tolerances govern the limits of relatability has not been comprehensively studied. (For some preliminary data and discussion on this point, see Kellman & Shipley, 1991.)

Experiment 3

The results of both Experiments 1 and 2 support the claim that a common process is responsible for unit formation in both illusory figures and partially occluded figures. Subjects' illusory figure clarity ratings quite accurately predicted their unity ratings for equivalent partially occluded figures and vice versa, but the displays used in both experiments were somewhat constrained. All of the displays contained the four corners of a four-sided figure. In principle our claim—that ratings in one type of display should predict ratings in the other—should apply to any illusory figure and partially occluded figure pair if their specified edges have been equated. Testing such a claim requires a random sample of the two types of displays taken from the entire figural space. Experiment 3 uses a set of displays in which the illusory and partially occluded figures have random shapes.

An algorithm was developed to generate random displays. The core of the algorithm is the ability to synthesize complicated wave functions from sine waves. By adding sine waves to the edge of a circle, we were able to synthesize figures with complex edges. The complexity of each figure was determined by the number of sines used to form its boundary. The shapes of such figures are determined by the amplitude and phase relations of the sine waves. Random figures were created by randomizing amplitude and phase relations for each figure.

Because the variation in figure extent from randomizing amplitude and phase was not always very large, a different method was used to generate the occluders. Occluders were generated by selecting at random the distance between the center and the edge of the figure at 200 equally spaced intervals. The resulting figures were smoothed slightly by averaging values of adjacent radians several times. By superimposing the occluders on the occluded figures, we were able to generate a set of random partially occluded figure displays. Equivalent illusory figure displays were derived from the occlusion displays using the methods described earlier.

Method

Subjects. Twenty undergraduates at Swarthmore College served as subjects in 45-min individual testing sessions. Each subject received $3 for participating.

Apparatus. Displays were presented on a Macintosh II computer with an E-Machines TX16 RGB monitor (25 × 33 cm). The screen's resolution was 34 dots per centimeter (860 × 1,024 pixels). All stimuli were presented to each subject in a random order (except where noted).

Subjects were positioned 50 cm from the monitor. The room was dark except for the illumination provided by the monitor.

Stimuli. The displays for Experiment 3 were generated by first creating a set of random occluded and occluding figures. Each random occluded figure was generated by adding sine waves of random amplitude (varying from 0 to 0.46 cm) and random phase around a circle (radius = 5.84 cm). As more sine waves were added, higher frequencies were used. The number of added sine waves ranged from 0 to 15 for a total of 16 displays. The addition of sine waves to a circle creates randomly shaped smooth figures, which are radially monotonic (no radian crosses the figure boundary more than once). The random occluders were generated by selecting radians of variable length (range = 0–13.13 cm) and then averaging adjacent radians five times to create a fairly smooth but irregular figure. Like the occluded figure, the occluding figure was also radially monotonic.

To create a matching illusory figures display, for any given partially occluded figure inducing elements were created that matched the edges of visible parts of the occluded figure. The boundaries of each inducing element were an inner edge determined by the extent and shape of each visible piece of occluded figure and two edges radiating away from the center of the display to the edge of the monitor. Figure 9 provides three examples of the partially occluded figure and illusory figure displays. The central figures in Figure 9a and 9b were created using 0, 7, and 15 sine waves.

Procedure. The instructions given to the subject were the same as those used in Experiment 1 with the following additions. After the subject had given their rating for the first illusory figure display, they were given these additional instructions:

> Please indicate the three locations in the figure with the clearest illusory contours. Remember that an illusory contour is the edge between the white areas. Please indicate the three clearest, starting with the clearest. [Pause to let subject respond.] Please also indicate the three locations where illusory contours are least apparent, starting with the least clear. [Subjects indicate these areas by pointing to them on the monitor. Their overall rating and reports of clearest and least clear edge locations were recorded for all 16 displays.]

Similar instructions were used for the partially occluded figure displays. After making their overall rating judgment, subjects were asked to do the following:

> Please indicate the three pairs of adjacent colored areas that most strongly appear to be part of a single figure. Please begin with the pair of adjacent areas that most appears to be part of a single figure. [Pause to let subject respond.] Please also indicate the three pairs of adjacent colored areas that least appear to be part of a single figure, starting with the pair whose members least appear to be part of a single figure.

Dependent Measures and Data Analysis

The overall figure ratings for the two display types were treated as in Experiments 1 and 2. Because each of the figures in Experiment 3 had a number of loci of edge interpolation with differing physically given edge orientations and positioning, it was felt that requiring only a single overall rating for each figure was somewhat arbitrary. For this reason, subjects' judgments of local edge clarity and unity were obtained. These results were analyzed by summing the number of times a particular location was reported as one of the three sites of strongest or weakest edge interpolation. Order (e.g., whether a selected location was the weakest or third weakest) was ignored. For each location, the total number of weak reports was subtracted from the total number of strong reports. This resulted in a score between −20 and 20 for each of the 189 locations in the two sets of displays. The correlation of scores on this scale between corresponding sites in equivalent occlusion and illusory figure displays was assessed.

Results

Overall ratings of unity of partly occluded figures and clarity of illusory figures closely corresponded. Figure 10 gives the ratings for each display. The correlation between mean ratings of equivalent occluded and illusory figure displays was .973 ($p < .01$). Individual subjects' correlations averaged .687 (range = .233–.917). Scores of local interpolative strength at the 189 individual locations correlated .848 ($p < .01$) between the occluded figure and illusory figure displays. Figure 11 shows a scatter plot of these data. Each point represents one location in a particular display.

Discussion

Experiment 3 extends the findings of earlier studies to a population of randomly generated displays. The displays were complex, irregular, and wholly unfamiliar to our subjects. Given the same arrangements of physically specified edges, interpolation seemed to occur in the same way for occlusion displays and illusory figure displays. This not only is true for complex figures rated as wholes, but the specific locations at which interpolation occurs strongly or fails to occur also appear to correspond closely in the two types of displays. These data contain a wealth of information about the specifics of the unit-formation process: What relations of orientation, alignment, and spacing support the interpolation of edges. These specifics are discussed in a forthcoming article; preliminary analysis suggests that the data support the model proposed by Kellman and Shipley (1991). For our present con-

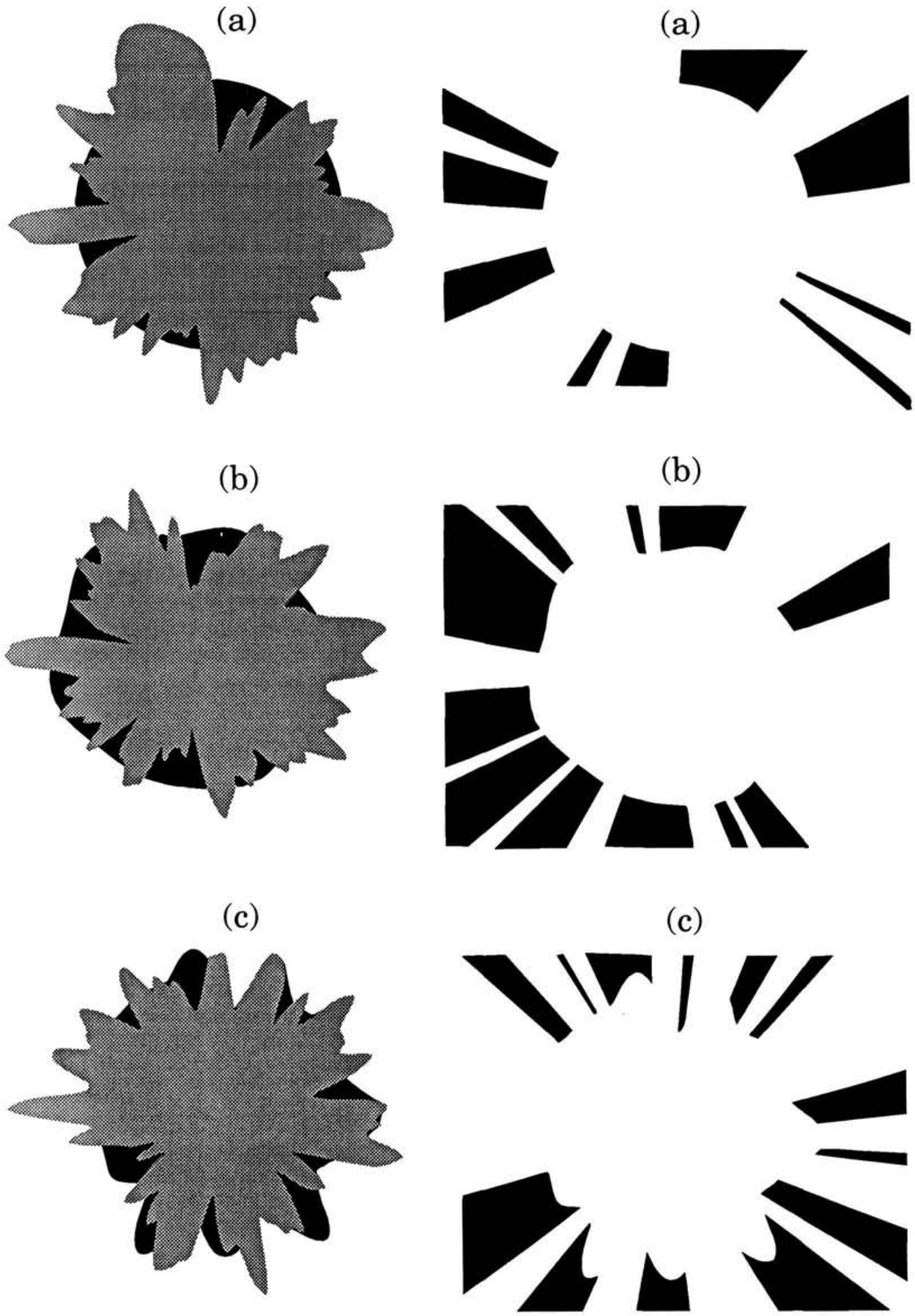

Figure 9. Examples of partially occluded figure displays and corresponding illusory figure displays used in Experiment 3: (a) no sine waves added; (b) 7 sine waves added; (c) 15 sine waves added.

cerns, however, the important result is that the same edge relationships, whatever they may be, appear to govern both occluded object and illusory figure formation. The results strongly support the identity hypothesis.

General Discussion

The results of these experiments support the notion of a single interpolation process underlying perception of bound-

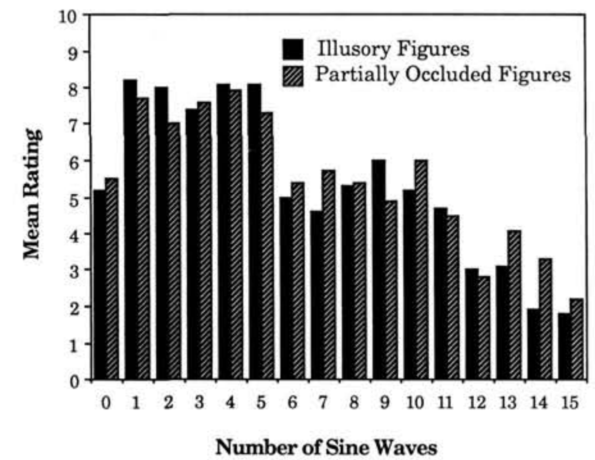

Figure 10. Mean ratings of unity for partially occluded figures and illusory figures as a function of number of sine waves used to create the occluded figure displays ($n = 20$).

aries that are not locally specified in occlusion and illusory figure contexts. Strength of interpolated edges in these two types of displays was found to be governed in nearly identical manner by the same variables. From the sampling of randomly generated displays, we can infer that any manipulations of position, spacing, and orientation of physically specified edges would lead to similar effects on perception of occluded figures and illusory figures.

These experiments also provide information about the process that produces interpolated edges. It is a process sensitive to relations of orientation and position of local edge

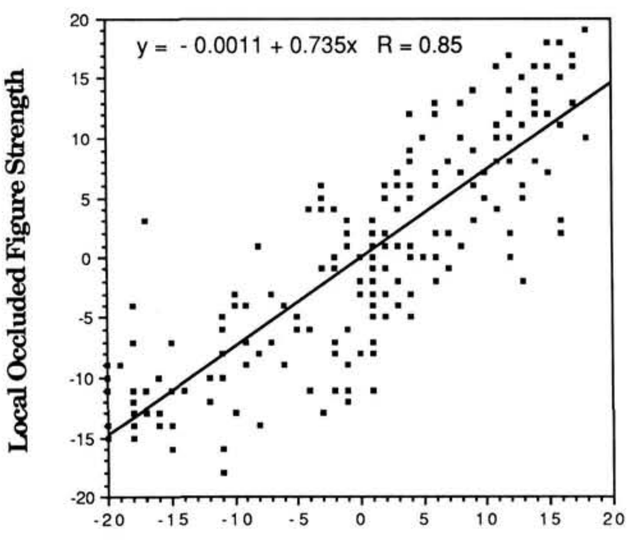

Figure 11. Local strength measure (the total number of strong reports minus the total number of weak reports) for individual locations in partially occluded figure displays plotted against the same local strength measure for illusory figure displays. (See text for detailed discussion.)

tangents. More specifically, although more comprehensive tests are needed, the data are consistent with the relatability criteria of Kellman and Shipley (1991).

Some investigators suggested that illusory figure perception depends mainly or partly on recognition of familiar figures (e.g., Wallach & Slaughter, 1988). Likewise, notions of global symmetry of outcomes have been invoked to explain unit formation in both occlusion and illusory figures (Van Tuijl & Leeuwenberg, 1982; for a discussion, see Kellman & Shipley, 1991). Experiment 3 in the present work is the first study of unit formation that we know of using randomly generated figures. The results unequivocally indicate that perception of both robust occluded objects and illusory figures can occur when familiarity is wholly absent and symmetry is minimal. Other research also casts doubt on the idea that such factors contribute to unit formation (Shipley & Kellman, 1990).

The present findings rest heavily on correlational data. Variables that affect the strength of boundary interpolation were found to have equivalent effects in occlusion and illusory figure displays. The strength of the case for a common process, considering these studies alone, derives from the very high concordance in perceptual reports for equivalent displays and the wide range of displays tested. The use of randomly generated displays in Experiment 3 makes it especially unlikely that the observed concordance is limited to fortuitously selected exemplars.

Correlational data alone, however, might be consistent with another hypothesis. Modal and amodal completion might be separate perceptual processes, but they might follow very similar rules. Several other considerations weigh against this possibility. First, bistable displays in which units switch between an amodal and modal appearance are better explained by an identity hypothesis. If separate processes were at work, the account of a bistable display would be convoluted. Referring to Figure 2, one would claim that initially the form seen in front is produced by a modal completion process and the one behind by an amodal completion process. At the time of reversal, these initial processes somehow stop operating, and the amodal process now affects the first figure just as the modal process takes over on the second. Somehow the switch between these two form-producing processes is accompanied by a switch in depth order as well.

This description seems to miss most of the interesting constraints on the phenomena. The displays in which reversals readily occur have very special properties. They are characterized by the absence of information specifying the depth order of certain surfaces. Moreover, in these cases the shapes of the units remain the same despite the switching; only the depth ordering (and the accompanying phenomenal appearance of which surfaces have sensory presence) changes. If one insists on two unit-formation processes here, it becomes a striking coincidence that the "form in front" process produces the same shapes as the "form behind" process.

A more parsimonious view disentangles the unit-formation process from the depth ordering of units formed. There is only one unit-formation process. This simplification, however logically appealing, would be unavailable if the units in the array or the shapes of interpolated boundaries changed when the modal–amodal switch occurred. Such changes do not appear to occur.

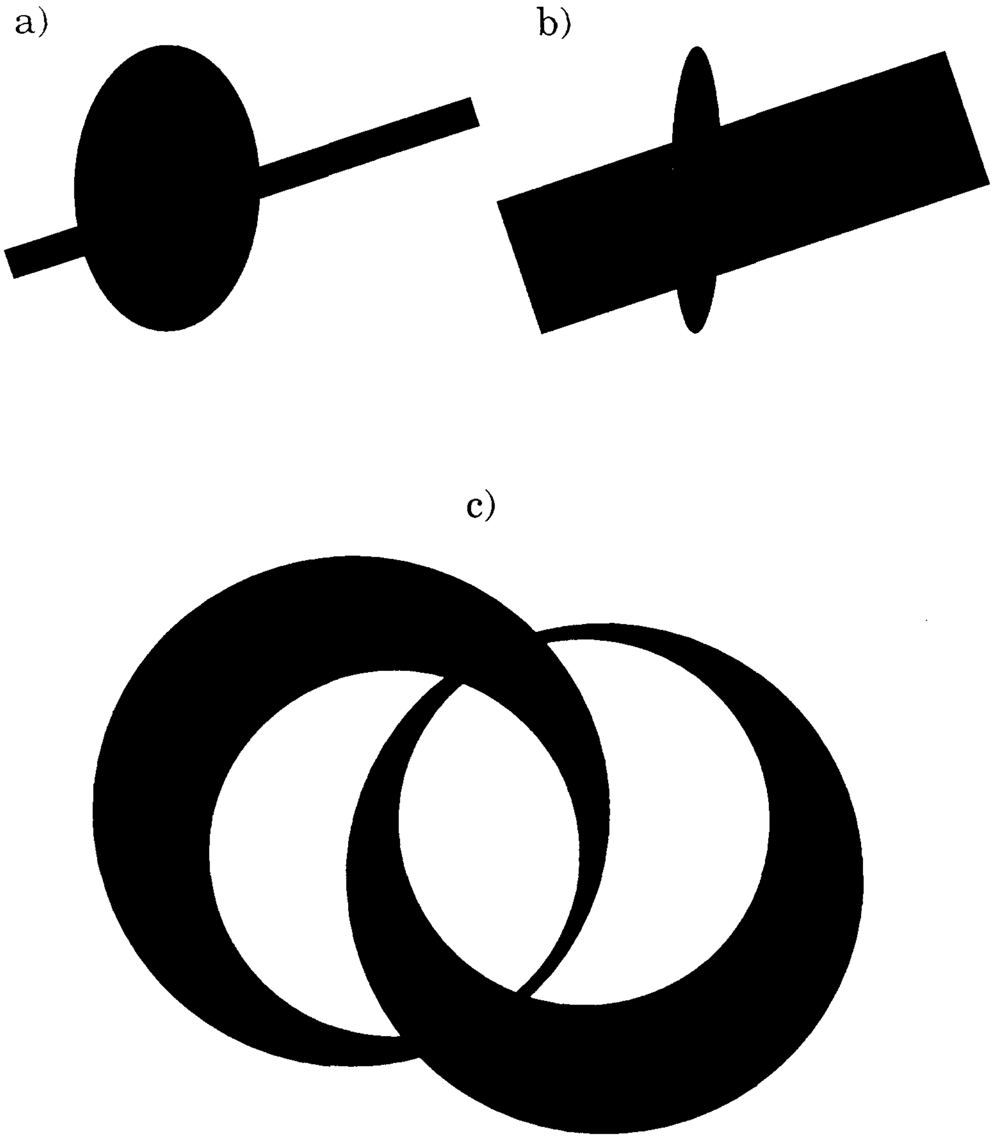

Figure 12. Some examples of spontaneously splitting figures illustrating the relationship between extent of interpolated edges and depth ordering: (a) Interpolated edges of the ellipse are shorter than those of the rectangle (the ellipse tends to appear in front with modal contours); (b) interpolated edges of the rectangle are shorter than those of the ellipse and tend to appear in front; (c) interwoven appearance of the two figures may be due to the relative extents of interpolated edges of each figure at the two areas of overlap.

Are there any cases in which the same physically specified edges might have differing effects on boundary interpolation depending on the depth relations of other surfaces? There does appear to be a class of such cases. Rock and Anson (1979) and Nakayama, Shimojo, and Silverman (1989) presented cases in which certain visible areas participate in unit formation when they are separated in the projection by an occluding object whose position closer to the observer is specified by stereoscopic disparity. When the same two views given to the two eyes are reversed so that disparity makes the central area appear farther away than other surfaces, unit formation may be blocked (Nakayama et al., 1989). Parks and Rock (1990) provided a similar demonstration in which pictorial depth cues determine whether or not an intervening edge affects interpolation.

The reason for this shift is not yet clear. A natural interpretation is that the classification of the edges of the intervening areas as occluding edges is necessary for the unit-formation process to operate. In other words, if a (projectively) intervening edge is classified as farther away than the edges that would normally support interpolation, then the unit-formation process is blocked. This idea does not seem to be correct, however, at least in its simplest form. Unit formation can occur in such cases. For example, Julesz (1971, p. 257) presented an example in which robust illusory contours form across a blank area between two random dot regions that are raised above the background surface (i.e., made nearer to the observer) by means of disparity information. A stimulus feature that appears to be crucial to the cases in which unit formation is blocked is the presence of competing edges or texture in the space between the relevant edges; the displays of Rock and Anson (1979), Parks and Rock (1990), and Nakayama et al. (1989) share this characteristic. Thus, the problem may have more to do with effects of edge competition on the interpolation process (Grossberg & Mingolla, 1985) than the effects of registering occluding edges. It may be that disparity assignment of intervening edges as being well in front of other surfaces allows unit formation to occur, whereas the absence of this type of depth separation does not. Kellman and Shipley (1991) suggested that specification of the inputs (physically given edges) in three-dimensional space may be important in determining relatability. It is possible that elaborating both the requirements of three-dimensional relatability and the effects of competition or interference on edge interpolation would explain the effects shown by Nakayama et al. (1989). Further investigation of these issues is needed.

Another issue raised by the notion of a single interpolation process concerns brightness effects on illusory figures. Some theories of illusory contours and figures proposed that processes of brightness perception cause these phenomena (Brigner & Gallagher, 1974; Jory & Day, 1979; Kennedy, 1978). There is some evidence that increasing contrast increases illusory contour clarity (Kellman & Loukides, 1987), although the effect is not large, and that illusory figures are not visible in equiluminant displays (Gregory, 1977; Livingstone & Hubel, 1987). In perception of partly occluded objects, because the occluded areas does not have sensory attributes, luminance effects have not been much considered or studied.

A number of lines of evidence converge to indicate that processes of brightness induction are not causal to illusory figures (de Weert, 1987; Kellman & Loukides, 1987; Parks, 1984; Rock & Anson, 1979). In fact, theories asserting causal status of processes of brightness perception seem to have been generally abandoned. A different sort of claim involving luminance may be more viable. The process of visual interpolation may require inputs of certain types; inducing edges specified by luminance differences are one type. It has been argued that chromatic differences alone are not sufficient to induce interpolation in either illusory or partially occluded figures (Livingstone & Hubel, 1987). It could also be that high-contrast edges make better inputs to the process than low-contrast edges. As far as we know, this idea has not been tested in occlusion contexts; evidence from illusory figure contexts suggests that such effects are modest (Dumais & Bradley, 1976; Kellman & Loukides, 1987). In any case, this idea is quite different from the claim that a brightness gradient must exist across illusory edges, a claim that is false (de Weert, 1987; Kellman & Loukides, 1987; Parks, 1984; Rock, 1987).

A single process underlies interpolation in occluded and illusory figures. Depth relations among the various projected surfaces in the array determine whether a given interpolated surface appears as partly hidden or as being in front of others. We close with an interesting question and a possible answer. In the absence of depth information, when interpolated edges cross how will the appearance be determined? Earlier we noted the phenomenon of spontaneously splitting figures in which homogeneous areas appear to be comprised of two separate objects. At the time, we noted the constraint that some depth order is always imposed and that it, along with the amodal versus modal status of the two figures, may reverse in some displays. Petter (1956) suggested an interesting constraint on these variations in appearance. The interpolated boundary that has the shorter extent of interpolation tends to appear in front (modally) with the other passing behind (amodally). Figure 12 gives several examples.

This rule about depth ordering of interpolated edges may be considered an extension of the depth cue of interposition. When neither physically specified edge continues through a discontinuity, the shorter interpolated edge appears in front. This formulation may be related to an earlier observation (Graham, 1929; Koffka, 1935) that smaller areas tend to be seen in front in reversible figure-ground configurations.

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