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Boundary completion in illusory contours: Interpolation or extrapolation?

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Abstract. Most computational and neural-style models of contour completion (ie illusory and occluded contours) are based on interpolation: the filling in of an edge between two visible edges. The results of three experiments suggest an alternative conception, that units are formed as a result of *extrapolation* from visible edges. In three experiments, subjects reported illusory contours between standard illusory-contour inducing elements and forms that do not, by themselves, induce illusory contours. We suggest that these forms are not a special case of inducing elements but that they represent a different class—*receiving elements*. Receiving elements are forms that can receive an illusory contour but cannot generate one, and they can alter contour formation. In experiment 1, receiving elements increased the judged clarity of illusory contours. In experiment 2, illusory edges were seen to connect to corners, line ends, and even the edges of circles. Boundary formation in motion displays also appears to be based on extrapolation. In experiment 3, subjects reported that small moving dots altered the formation of spatiotemporally defined boundaries. Implications for higher-order operator and network models of boundary formation are discussed.

1 Introduction

The remarkable optics of the human eye capture, from any vantage point, a detailed projection of the visible environment. Given a sufficient description of the three-dimensional layout, it is a straightforward matter to use projective geometry to compute how it maps onto each retina. A less well understood scientific task is the reverse: computing how accurate descriptions of the viewed objects and arrangements can be gotten from these optical projections.

One of the major contributors to this 'inverse optics' problem is occlusion. Because of occlusion, a given object may project to multiple locations on the eye; yet we are able to see complete objects. The various visible patches projecting from a single object appear connected behind the occluding areas. This phenomenal experience is the result of visual unit formation processes that link visible edges and surfaces. In a related type of display—illusory figures—the linkage is experienced as visible connections going in front of other surfaces.

There are a number of models of how humans perceive separate visible image pieces as parts of a single coherent object. While details vary, the models typically incorporate explicit interpolation or filling-in processes. Although both edge and surface interpolation processes play a role in perceptual unit formation (Grossberg and Mingolla 1985; Kellman and Shipley 1991), edge processes are the primary contributors to representations of shape (Kellman et al 2001).

Edge-interpolation models characteristically require real-edge inputs (eg given by contrast, texture, stereoscopic disparity, or motion) on either side of a gap. Edge fragments in certain relations and meeting certain constraints give rise to a representation of the intervening edge. For example, in Grossberg and Mingolla's BCS (boundary contour system) model (Grossberg and Mingolla 1985) boundaries are constructed between visible edges as a consequence of the activation of bipole operators (a unit whose activity depends on the input to two spatially discrete regions). The bipole operator may be found in a number of models. In the model of Heitger et al (1998), edge activation at intervening points depends on the multiplicative contributions of two separated lobes of a grouping field. The multiplicative relation implies that both lobes must have non-zero activation for the operator's output to be non-zero (Heitger et al 1998). For Kellman and Shipley (1991), contour completion requires *relatable* edges, ie a pair of real edges must meet certain geometric conditions, such that the interpolated edge would be smooth, monotonic, and would not bend more than 90°. [A detailed review of these, and related models, can be found in Kellman et al (2001).]

All these models of interpolation share a dependence on *pairs* of physically given edges. We will reserve the term *interpolation* for processes that have this property. While interpolation can account for many aspects of illusory-contour and occluded-contour perception, some phenomena are hard to explain by interpolation. Figure 1a shows an example of a phenomenon described by Kanizsa (1979). Observers reliably misperceive the size of the visible area of the gray rectangle. The gray rectangle on the left will probably appear to most closely match the middle rectangle on the right even though the second from the top is the correct physical match. In general, observers overestimate the area of the gray rectangle by 8% (Kanizsa 1979). Kanizsa argued that this illusion, as well as a number of related illusions, results from boundary extension where one form appears to extend under another. While one might offer alternative accounts of this phenomenon, it would be difficult to provide an explanation of extension in terms of interpolation, because it occurs despite the absence of a second visible edge to join the extension. The term *amodal continuation* describes this phenomenon, distinguishing it from completion or interpolation, in which two visible contours or surfaces join behind an occluder.

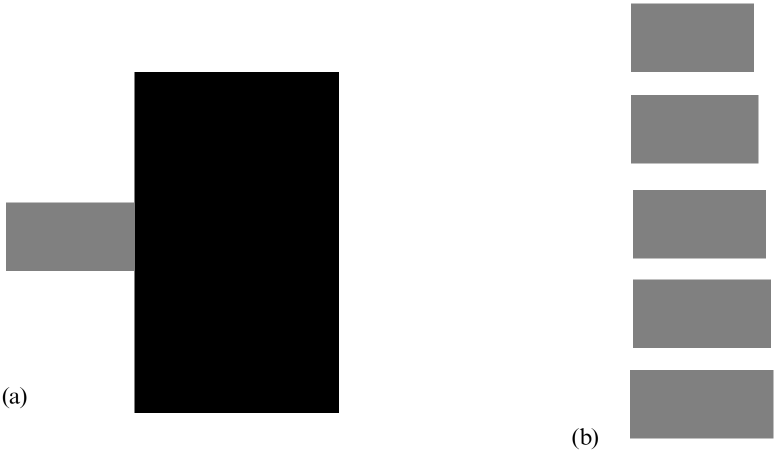
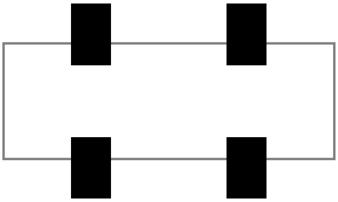


Figure 1. Demonstration of amodal continuation. In the display on the left (a), the area of the gray rectangle is usually overestimated. The effect can be seen if one attempts to select the display in (b), on the right, matching the gray rectangle on the left. (The second rectangle from the top matches physically, but observers generally choose the third rectangle from the top.) After Kanizsa (1979).

Shimojo and Nakayama (1990) also found evidence of amodal continuation. They used perceived direction in an apparent-motion paradigm to infer the location of object boundaries. The two frames shown in figure 2a alternated in apparent motion. The motion of the small square is potentially ambiguous: the squares can appear to be moving vertically or horizontally. If the horizontal and vertical distances are equated in such a display, without an occluder, the direction of motion is bistable—the squares

(a)



(b)

Figure 2. (a) An illustration of the two-frame apparent-motion display used by Shimojo and Nakayama (1990). (b) The small squares in frames 1 and 2 are seen to extend under the adjacent gray rectangle, and consequently, the vertical gap between them is smaller than the horizontal gap. After Shimojo and Nakayama (1990).

could appear to move vertically or horizontally. When one gap is smaller than the other, direction of motion will favor the smaller gap (cf Ullman 1979). With the rectangle present, subjects tended to see vertical motion, and a substantial increase in the vertical spacing was necessary before horizontal motion was reported. This suggests that the vertical pair were represented as being closer than the horizontal pair. Shimojo and Nakayama concluded that this phenomenal proximity was the result of the boundaries of the squares extending vertically under the rectangle (illustrated in figure 2b). The amodal continuation decreased the phenomenal vertical separation of the objects.

Closely related to these phenomena are certain interactions of contour and surface interpolation processes. Yin et al (1997, 2000) studied a surface interpolation process that complements contour interpolation by linking partly occluded areas based on similarities in their visible surface characteristics. *Surface spreading* under occlusion is confined by real and interpolated boundaries. One phenomenon exploited in experimental work is that a form that appears as a spot on a surface can be made to appear as a hole. In figure 3a, two identical spots appear in different places in a black surround. Ordinarily, spots would appear as figures in front of a background (Rubin 1915). The spot to the right does appear to be in front. The spot on the left, however, has a different appearance: it looks like a hole in the surface, owing to its projective position within the confines of interpolated and real edges (of the ellipse). The surface interpolation process under occlusion allows the gray circle to be connected to the visible gray portions of the ellipse (Yin et al 1997).

(a)

Figure 3. Two examples of surface completion. In (a) surface completion occurs within the interpolated contours of the ellipse. In (b) surface completion occurs within the extended boundaries of the rectangle.

Most relevant to our immediate concerns is figure 3b. Here, the visible gray area at the top does *not* connect by contour interpolation to any other visible area. Thus, the spot below it does not fall within real or interpolated edges of a gray surface. Nevertheless, this spot appears as a hole in the black surface. By contrast, the spot on the right does not. Kellman and Shipley (1991; Yin et al 1997) proposed that surface spreading occurs not only within interpolated edges, but also along the linear extensions of visible areas that are interrupted by occlusion.(1) Experimental results confirm this effect (Yin et al 1997). These results fit with those of Kanizsa (1979) and Shimojo and Nakayama (1990) in suggesting that some boundary continuation process occurs even in the absence of interpolation.

Amodal continuation is not the only indication of contour processes not fully captured by interpolation-based models. Several investigators (Day and Jory 1980; Gregory 1972; Kanizsa 1955/1987; Minguzzi 1987; Sambin 1987), have reported that the inclusion of small elements substantially alters the appearance of illusory-figure displays. Figure 4a shows an example. The robust illusory square seen in figure 4a depends on the dots, as can be verified by comparison with figure 4b, where an illusory circle is generally seen. The effect shown in figures 4a and 4b would be unremarkable if the dots themselves were illusory-contour inducing elements. Obviously, changing the location or number of inducing elements will change the shape and/or the strength of illusory forms (Lesher and Mingolla 1993; Petry et al 1983; Shipley and Kellman 1990). However, these four dots alone do not function as inducing elements, producing no illusory contours when presented alone (figure 4c). For descriptive convenience, we label pattern elements that have these characteristics illusory-contour *receiving elements*. Phenomena involving receiving elements are problematic for simple interpolation-based models, where all interpolated contours must connect pairs of inducing contours. In particular, the requirements for inducing elements include physically specified edges, leading into tangent discontinuities (Shipley and Kellman 1990), and interpolation is highly dependent on the orientations and positions of the inducing edges. A dot contains no tangent discontinuities or oriented edges, so its presence should not affect interpolation. Therefore, it is not clear how different illusory forms could be seen in two displays that have the same discontinuities and relatable edges.

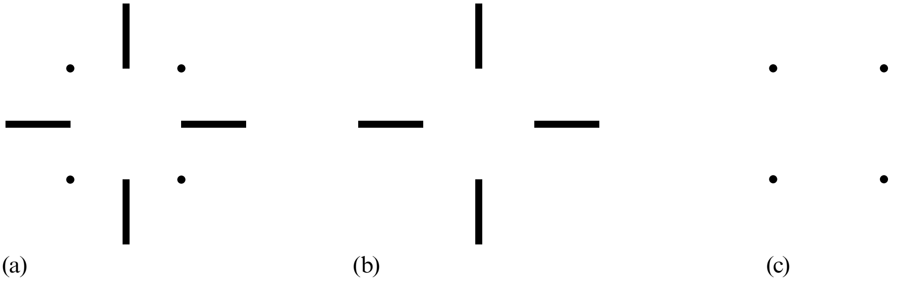


Figure 4. An illustration of the effect of adding small dots to an illusory figure display (see text).

2 Experiment 1

The existence of receiving elements, such as dots, that cannot by themselves produce illusory contours, but that influence their locations and clarity, suggests that interpolation models must be incomplete. Or, put another way, receiving-element phenomena may provide important clues about the mechanisms that accomplish contour interpolation. While the displays created by Kanizsa and others have raised these issues, the

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(1) The exact role of the small circles is not yet clear. We do not know if they promote more surface extension than would occur in their absence. Nevertheless, it is clear that by themselves the circles do not result in surface spreading.

demonstrations have been restricted to adding dots to illusory-figure displays. Moreover, as far as we know, there are no systematic experimental investigations of receiving-element phenomena. Experimental methods are needed to assess the specific nature and the range of effects of receiving elements.

The purposes of experiment 1 were to see if the set of forms that function as illusory-contour receiving elements extends beyond dots, and to test perceived contour strength in such displays. Subjects were tested with the displays shown in figure 5. To study a variety of possible receiving elements, we used pattern elements that have previously been shown to produce negligible or, in some cases, weak illusory edges (middle row).(2) These were combined with inducing elements that formed illusory figures with weak to moderate edges (top row). The resulting displays are shown on the bottom row. The receiving elements in the middle all come from previous work (Day and Kasperczyk 1983; Kanizsa 1955/1987; Kennedy 1981; Shipley and Kellman 1990). Two of these have been tested in magnitude-estimation paradigms for contour clarity. When a very clear illusory-contour display—eg the classic Kanizsa triangle—is given as a modulus having an assigned rating of 10, the crosses received ratings of 2.8 to 5.0, and the circles 0 (from Day and Kasperczyk 1983; Shipley and Kellman 1990, respectively).

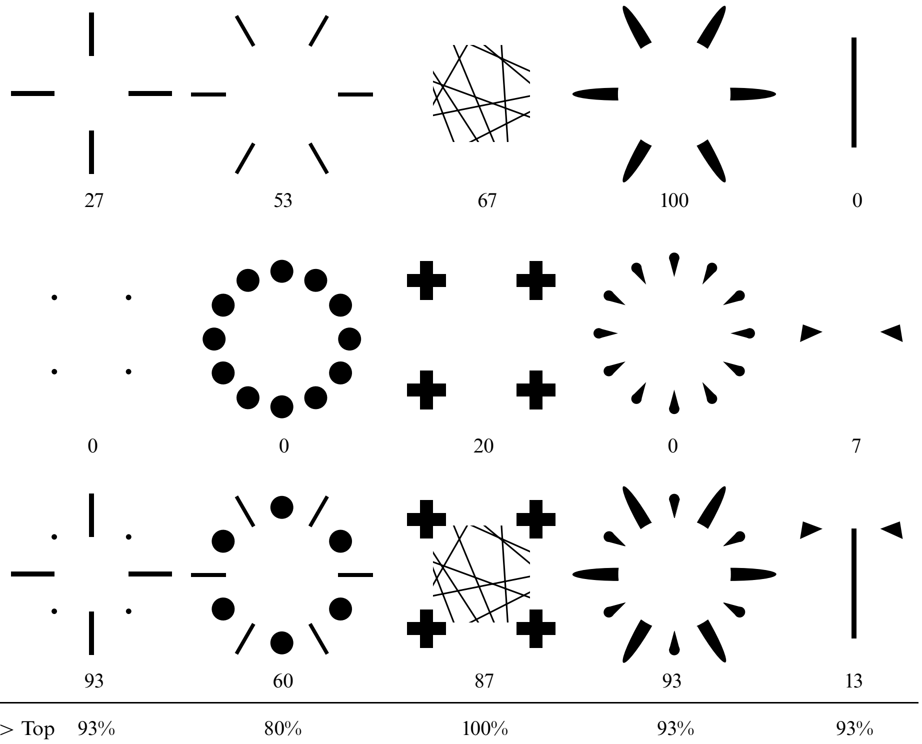

Figure 5. Illustration of the figures used in experiment 1. Below each figure is the percentage of subjects who reported seeing an illusory form. At the bottom is the percentage of subjects who reported the illusory figure in the bottom row to be clearer than the corresponding illusory figure in the top row.

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(2) To be sure that any absence of illusory contours for displays in the middle row was not due to a small number of elements, we tested two configurations of the second and fourth displays. In one configuration, not shown, displays had the same numbers of receiving elements as were present in the combined displays. In the other configuration, shown here, twice as many elements were used, so the middle and bottom rows were matched for total number of elements. The results for the two configurations did not differ.

2.1 *Methods*

2.1.1 *Subjects.* A group of fifteen Temple University undergraduates participated in the experiment as partial fulfillment of requirements of an introductory psychology course.

2.1.2 *Stimuli.* Displays were created with Adobe Illustrator and printed on individual white cards. For the present – absent task a single display was printed in the center of the card. For the pairwise judgment task, pairs of illusory-form displays were presented so that the potential illusory edge would be 2 cm to the left and right of a small (1 cm) fixation cross positioned in the center of the card. The length of illusory edge in the four-dot displays (figure 5, leftmost column) and single inducing-element displays (figure 5, rightmost column) were equated; in both the gap was 1 cm. For the four-dot display, the inducing elements were 1 cm long and 0.1 cm wide, and the receiving elements were 0.1 cm diameter. For the single element display, the inducing element was 2.5 cm long and 0.1 cm wide, and the receiving elements were 0.5 cm wide and 0.3 cm high. For the other three displays, the size of the central form was equated. For displays in the second column from the left, the inducing elements were 1 cm long and 0.1 cm wide, and the receiving elements were 0.5 cm diameter. For displays in the third column, the inducing elements were thin lines that spanned the 2.5 cm by 2.5 cm square, and the receiving elements were 1 cm by 1 cm crosses with arms that were 0.33 cm long. For displays in the fourth column, the inducing elements were 1 cm long and 0.3 cm wide (along the contour of the circle), and the receiving elements were 0.5 cm long. For the viewing distance used in experiments 1 and 2, 1 cm is 0.95 deg of arc. In experiment 1, individual displays ranged from 2.38 deg to 4.77 deg in diameter.

2.1.3 *Design and procedure.* Subjects viewed the cards, without head restraint, from 60 cm away. They made forced-choice, present – absent judgments whether an illusory form appeared in each of the displays shown in figure 5. They also made pairwise comparisons between the forms shown in the top and bottom rows of figure 5. Half the subjects made the present – absent judgments first and the other half made pairwise comparisons first.

For the present – absent judgments, subjects were shown a Kanizsa triangle display and the experimenter indicated the illusory contours. They were then shown the set of displays and asked for each one to indicate whether an illusory form was present or absent. For the comparisons between illusory forms, subjects were shown a Kanizsa triangle and a line outline of the Kanizsa triangle display. The experimenter explained that while one could imagine that a triangle was present in the outline display, one was clearly visible in the filled-in display. Subjects were then shown the display pairs from figure 5 and instructed to pick the display with the clearer illusory figure. They were instructed to look at the fixation cross when they made their decision.

2.2 *Results and discussion*

The percentage of subjects who indicated they saw an illusory form is shown below each item in figure 5. The percentage of subjects who indicated the illusory form in the bottom row was clearer than the one in the top row is given along the bottom of figure 5.

The results for four lines and four dots, the leftmost set in figure 5, is consistent with previous discussions of this display (Day and Jory 1980; Gregory 1972). While this set offers the most dramatic increase from the display on the top row to the bottom row, the other displays show the same pattern (with the exception of the second from right; in this case, the top row was at ceiling).

The results of the pairwise comparisons were consistent with the present – absent judgments, subjects overwhelmingly judged the combined displays to be clearer than the basic illusory-contour displays (top row). The rightmost column is particularly interesting in this regard as only two subjects spontaneously reported seeing contours in the combined display, but almost all of the subjects reported the combined display to be clearer than a single inducing element.(3) The consistent relative clarity judgments suggest that a contour was seen in this display; however, it was presumably so weak that for most of our subjects it did not meet their individual criterion for reporting an illusory figure. Given the possibility that a threshold is used for the present – absent judgments, it is impossible to definitively conclude that receiving elements, such as dots, circles, and tear drops, are not very weak inducers of illusory contours. However, given available information, we know of no cases in which these elements alone generate contours. For example, the second displays in the middle row of figure 5, studied by Shipley and Kellman (1990), have a dense spacing of elements; yet, compared to a display with fewer elements, contour induction seems no different. As mentioned, the display shown received consistent zero ratings in earlier research. What is clear is that receiving elements have an important property: they can receive contours.

3 Experiment 2

That some forms can influence illusory-figure formation, yet not initiate boundary formation, suggests that only one end of an illusory edge needs to be an inducing element with discontinuities. A plausible idea about receiving elements, then, is that they can anchor or receive an illusory contour. Experiment 1 indicated that receiving elements include a variety of forms, including dots, circles, crosses, tear drops, and triangles. In experiment 2, we sought to establish some of the characteristics that allow forms to serve as receivers. To do this we asked subjects to report whether or not they saw an illusory edge in displays with a single inducing element. The results of experiment 1 suggest that corners and edges can serve as receivers. Experiment 2 sought to verify this with a larger set of forms and to identify forms that cannot serve as receivers.

3.1 *Methods*

3.1.1 *Subjects.* A new group of twenty Temple University undergraduates served as subjects in experiment 2.

3.1.2 *Stimuli.* To generate the experimental displays, two types of inducing elements were used, a single narrow rectangle similar to the ones used by Day and Jory (1980) and a semicircle. The rectangular inducing elements were 2 cm long and 0.2 cm wide. The semicircle had a diameter of 1 cm. Eleven forms were presented 0.5 cm on either side of the inducing elements to see if they would receive contours from the single inducing element. These ranged in size from 0.1 cm dots to a 2 cm diameter form with many small projections. Displays varied in width from 0.95 deg to 5.7 deg. Figure 6 shows the displays used in experiment 2.

3.1.3 *Design and procedure.* The viewing conditions and the forced-choice, present – absent task used in experiment 2 were the same as those used in experiment 1.

3.2 *Results and discussion*

Beside each display in figure 6 is the percentage of subjects who reported seeing a contour. The response rates ranged from a high of 75% reporting an illusory edge in the display with small dots as receivers (figures 6a and 6b), to a low of 5% reporting an edge when the potential receiving elements contained many small projections (figure 6o). Overall, the semicircle yielded more illusory-contour reports than the thin rectangle ($p < 0.05$, exact probability). The two shapes showed a similar pattern of responding across the potential receivers ($r = 0.77$).

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(3) While there is little evidence that an illusory edge can be seen in monocular displays with a single inducing element, in stereoscopic displays it is clear that a single inducing element with a half-occluded contour can result in an illusory edge (Anderson 1994).

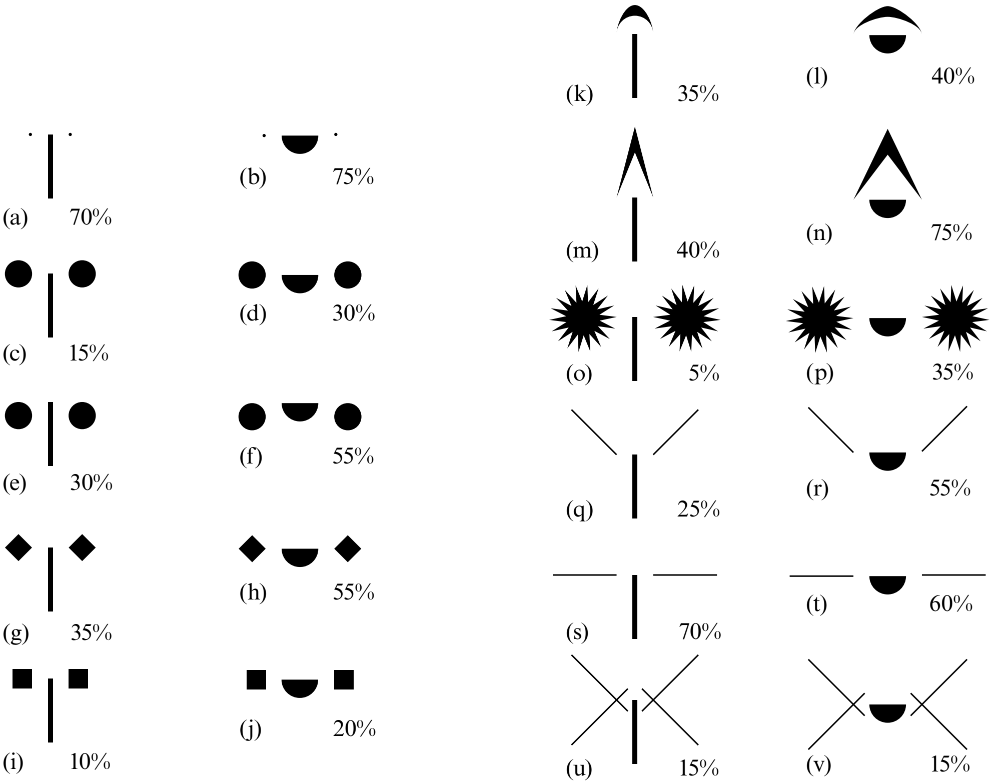

Figure 6. Displays used in experiment 2 (see text).

When the small dots in figures 6a and 6b were expanded into circles which have smooth edges and determinate edge orientation, as in figures 6c and 6d, the number of illusory-contour reports significantly decreased ($p < 0.05$).(4) The location of the potential receiver elements appears to be important. The edge of the form appeared to offer better support for contours than the center of the form (compare figures 6c and 6d with 6e and 6f; $p < 0.05$). This finding suggests that extrapolation to a receiving element is most likely when the extrapolated edge meets a similarly oriented luminance-defined edge, and avoiding a discontinuity in edge orientation (in the case of a dot, which has no preferred orientation, it can anchor an edge coming from any direction).

While the center of a square and a circle offered similar poor levels of support (figures 6c, 6d, 6i, and 6j), the corner of a square offered significantly better support ($p < 0.05$). Corners of different forms offered similar levels of support (figures 6g, 6h, 6k, 6l, 6m, and 6n) despite differences in the orientation of the contours that form the corner. It would appear that many tangent discontinuities in close proximity did not offer good support (figures 6o and 6p); this may reflect competition among the discontinuities. Others have also found that multiple discontinuities reduce the appearance of illusory contours. (Some examples may be found in Rock and Anson (1979), although they did not interpret their findings in this way.) Finally, line ends (figures 6q, 6r, 6s, 6t) offer better support than the crossing point of two lines (figures 6u and 6v) ($p < 0.05$). This is not entirely surprising, as line ends can serve as inducing elements; however, illusory contours usually appear perpendicular to the inducing line, and do not appear parallel to a line, as in figures 6s and 6t (Kennedy 1978).

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(4) All *p*s are exact probabilities for difference in proportions, with the number of reports in the rectangle and semicircle displays combined.

The overall response rates are relatively low compared to the percentages of subjects who would likely report edges in common illusory-contour displays, such as the Kanizsa-triangle display. However, the critical finding here is that subjects reported any contours at all in these displays. Subjects often reported seeing illusory edges between a central inducing element and the adjacent forms—the receiving elements.

Can the set of potential receivers be characterized in any simple way? The data suggest that, in addition to dots, tangent discontinuities (ie contour-orientation discontinuities), even those that do not serve as inducing elements, can act as receivers. Smooth contours do not serve as receivers, or serve to a lesser extent, except when the smooth contour is tangent to an illusory edge. Tangent discontinuities may act as receivers because edge orientation at a corner is unstable or undefined, and so an extrapolated contour may link with a luminance-defined contour without introducing a discontinuity. This account of the data has the virtue of connecting receiving elements to the initiating conditions for interpolation. Whereas tangent discontinuities in oriented edges play a crucial role in initiating interpolation (Shipley and Kellman 1990), tangent discontinuities alone (in the absence of suitably oriented edges) can serve as receiving elements.

4 Experiment 3

The purpose of experiment 3 was to extend the investigation of how contours are completed to the domain of moving forms. Shipley and Kellman (1993, 1994, 1997; Shipley and Cunningham 2001) have described a process, spatiotemporal boundary formation (SBF), which shares a number of properties with boundary formation in static displays. In dynamic accretion–deletion displays, as would be generated, for example, by a textured form passing over a surface with similar texture, a form is seen. Here the boundaries are defined solely by the appearance and disappearance of small texture elements (Gibson et al 1969), as is evident by the disappearance of the form when the display stops. Clear, continuous boundaries and well-defined shape are seen in such displays even when texture density is low. Motion of an occluding surface is not necessary; boundaries may be seen even when there is no motion of elements in the display (Shipley and Kellman 1994). What is necessary is the presence of abrupt changes in the appearance of small elements. These can include accretion and deletion of the elements, but they also include changes in color, shape, orientation, or position. In general, these abrupt changes in element appearance may be considered spatiotemporal discontinuities. Spatiotemporal discontinuities serve a role that is analogous to the role of static discontinuities in illusory-contour and partially occluded figure displays (Kellman and Shipley 1991). In both cases, the discontinuities are localized, visible features that are potential indicators of occlusion. They will invariably occur when one form covers another. We have argued that interpolation processes use these spatiotemporal discontinuities as a starting point to initiate computations of the boundaries of moving occluding forms (Shipley and Kellman 1993).

As in the static case, this process completes a smooth, continuous boundary between discontinuities. In a forced-choice shape-matching task, Shipley and Kellman (1994) found that subjects systematically confused a hexagon for a circle, but not vice versa, at low element densities. Only in higher-density displays was the hexagon seen. The circle was seen in the low-density displays, while the hexagon was not, because the small number of spatiotemporal discontinuities did not closely constrain the shape of the moving form and the completion process yielded smooth, curved, boundaries. How are the boundaries between fragments completed? Is the process based on interpolation or extrapolation? If the process is based on extrapolation, then we might expect to find that some elements or events affect the shape of the spatiotemporally defined forms, even though they do not produce spatiotemporal boundary formation in isolation.

Bradley (1982) created an animated display in which an opaque triangle rotated over three lines. When dots were placed at the vertices of the triangle, well-defined edges were seen. While this demonstrates that this effect can occur in dynamic displays, it is not clear that this is an example of SBF as static discontinuities were present, so an illusory triangle would have been seen in each static frame.

For our test, we created an SBF display that was analogous to the static display developed by Kanizsa (1955/1987). Like the static display, this display was based on an SBF display where a weak circle was seen moving around the screen (this is illustrated in figure 7a). To this display, a set of small dots was added that moved with the spatiotemporally defined circle (see figure 7b). Such moving dots do not appear to result in phenomenal boundaries. If SBF is the result of extrapolation, then boundaries may be seen linking to the additional moving elements.

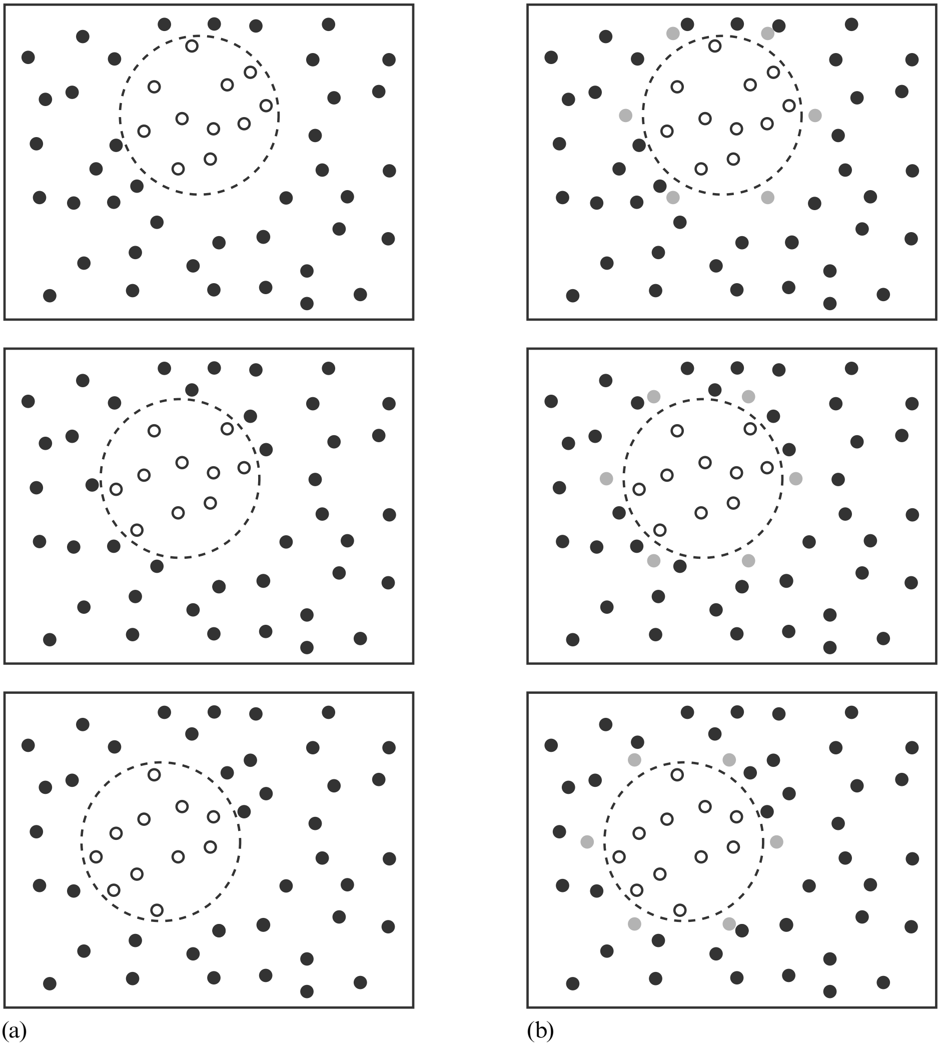

Figure 7. An illustration of three frames from the SBF displays shown in experiment 3. In (a), elements sequentially appear and disappear (illustrated as open circles) as the invisible circle (illustrated with a dashed line) moves over them. The same display is shown in (b), with six additional elements moving with the circle; for this illustration these dots are shown in gray, in the actual displays all elements were the same color.

4.1 *Method*

4.1.1 *Subjects.* A new group of twenty-five Temple Undergraduates served as subjects in experiment 3.

4.1.3 *Stimuli.* The basic SBF display simulated a 10 cm black circle (4.7 deg diameter) that moved over and occluded an array of small white elements on a black background (figure 7a). One hundred elements were randomly distributed over the entire 30 cm by 30 cm field (a density of 1%). SBF is evident in such low-density displays but boundary formation is not at ceiling (Shipley and Kellman 1994). To create the second display, six dots were added that translated with the circle (figure 7b). The dots formed a regular hexagon and were located 10% of the diameter outside of the circle. The third display had just the six moving dots.

4.1.3 *Design and procedure.* Subjects were shown each of the three displays, in a random order, and asked to report what they saw. If subjects reported seeing a moving form, they were asked if they could see all of the boundaries. Viewing distance was 120 cm. Subjects' responses were coded for whether or not they reported a moving form. If they saw a form, responses were further categorized into circle, hexagon, or other.

4.2 *Results and discussion*

In the basic SBF display, 84% of the subjects reported seeing a circle moving over a background of stationary elements. When six dots were added, 80% of the subjects then reported seeing a hexagon with complete edges that extended between the moving dots. No shape or edges were reported in the display with just six moving dots. Note that the spatiotemporally defined form was always a circle. When the six dots were added, the subjects reported a form that was inconsistent with the optical pattern of changes; they saw a hexagon. It would appear that the moving elements were linking with, or receiving, the edges that would have formed into a circle. This suggests that boundary formation in dynamic displays is based on extrapolation. The abrupt changes in element visibility served to initiate contour formation and the moving dots serve as receivers.

In the static case, a difference between inducers and receivers is that inducers have visible, oriented edges and receivers (eg dots) need not. In SBF, there are no physically given oriented edges that make up parts of the figure. Shipley and Kellman (1994, 1997) argued that the SBF process itself establishes the oriented contour fragments. Continuous boundaries are then produced by ordinary relatability between these edge fragments.(5) Moving dots can receive boundaries from spatiotemporally defined boundary fragments, just as static dots do in illusory-contour displays.

5 General discussion

Receiving elements, such as dots, can alter contour formation in static and dynamic displays. Perceivers report illusory boundaries that extend between conventional inducing elements and receiving elements. Experiment 1 verified these effects. In experiments 1 and 2, we found that dots are not the only forms that can cause this effect: illusory edges may connect to corners, line ends, and even the edges of circles. Receiving elements, when presented between inducing elements, can increase the apparent clarity of an illusory edge. These forms do not seem to be weak inducing elements; they represent a different class of elements, receiving elements—forms that can receive an illusory contour.

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(5) One complication in moving displays is that moving boundaries may be specified at different points in time. The completion mechanism appears to discount the motion to identify the relative location of the fragments (Palmer et al 1997, 2000).

These findings raise important questions about interpolation mechanisms. Neural-style models of contour interpolation have most often relied on cooperative or bipole-type units that require non-zero inputs on both sides of a gap (Grossberg and Mingolla 1985; Heitger et al 1998). It is not clear that such units could account for the phenomena of amodal continuation in occlusion or the effects of receiving elements in illusory-contour displays. Regarding amodal continuation, the problem is that it is impossible to clap with one hand: in the absence of a second, properly located, edge, the neural-style models seem to predict that a boundary should not be seen to extend behind an occluder. Regarding receiving elements, our results confirm that these can change the paths of interpolated contours and produce new contours if paired with single inducing elements.

The latter result could be handled by bipole units if it is hypothesized that dots or other receiving elements produce a small amount of activation in one lobe of the bipole. Then, the multiplicative interaction between activation in the two lobes could be non-zero. There would appear to be several difficulties to be resolved in such an explanation, however. One is that bipole operators are ordinarily said to be sensitive to edge orientation as well as position; yet small dots, which make good receiving elements, have no preferential orientation. Dots could activate detectors across the range of orientations, so the success of a particular model may lie with how it handles inhibition between detectors tuned to different orientations. Second, in cases where a bipole unit does have strong inputs on both lobes, why should the presence of a dot influence the perceived path of interpolation? It is possible that these issues could be resolved in terms of the weightings of different parts of the receptive fields of the bipole lobes. Specifically, our informal observations suggest that the ability of dots to modify a path given by interpolation is stronger when the dot falls near the linear extension of an edge and the interpolated path curves substantially (ie the interpolated path is not collinear). Given that strength of interpolation decreases with deviation from collinearity (Field et al 1993; Kellman and Shipley 1991), these effects might be handled by the weighting field in the lobes of bipoles. Perhaps the more difficult challenge is understanding how amodal extension can occur.

An alternative idea may produce a better account of the phenomena of receiver elements and amodal continuation. Broadly speaking, there are two general ideas about how interpolation proceeds: the bipole or 'higher-order operator' notion and the idea of lateral interactions of orientation-sensitive units within a single network (Kellman et al 2001; Ringach and Shapley 1996). Each of these ideas has strengths and weaknesses in accounting for interpolation phenomena (see Kellman et al 2001 for discussion), and theories may ultimately need to incorporate both notions. In the present context, the network idea appears to fit some phenomena more naturally. The basic idea is that at some early level of cortical visual processing (eg V1 or V2) orientation-sensitive units activated by the stimulus send activation to their neighbors along paths described by particular geometric relationships (Field et al 1993; Kellman and Shipley 1991).

This idea has been elaborated in connection with contour *integration*—the establishment of contour tokens by linking adjacent, stimulus-activated, orientation-sensitive units (Yen and Finkel 1998). At the heart of this idea are lateral interactions among oriented units in a single layer; there is substantial neurophysiological evidence to support such interactions (eg Gilbert 1994). Network models could be generalized from contour integration to interpolation. In fact, some studies concerned with contour integration have utilized oriented segments separated by gaps (Field et al 1993), suggesting a close relation between contour integration and interpolation.

Perception of clear interpolated contours may well require that activation sent out by a stimulated unit merge with activation from another unit. However, in the absence of such a 'destination' unit, the activation from a single unit may account for amodal continuation along linear, extended paths and for the phenomena of receiver elements in our experiments.

In short, interpolation may originate with contour extrapolation. Inducing elements, necessary for illusory contours, may send activations out along their linear extensions and less so along a family of nearby directions. Although the strongest interpolated paths will result when activations from two sources meet, a variety of elements that do not send their own activations can receive and anchor activations. When contours are received, modest illusory edges are seen.

This idea is illustrated in figure 8. In illusory-contour displays that contain two inducing elements, edges are extrapolated from each boundary fragment; this is illustrated in figure 8a by a set of arrows radiating from the corners of the two edges, indicated by black rectangles. This fan of arrows is similar to the diagram by Field et al (1993) of an 'association field'. The geometry for such a field is given by the constraint of contour relatability (Kellman and Shipley 1991). It can be verbally expressed in terms of two conditions. First, a complete interpolated path must not change in direction by more than 90° (suggesting that extrapolations are confined to ±45°). Second, a connection between arrows occurs only if two edges coming from opposite directions have the same slope and the second derivative with the same sign when they meet.

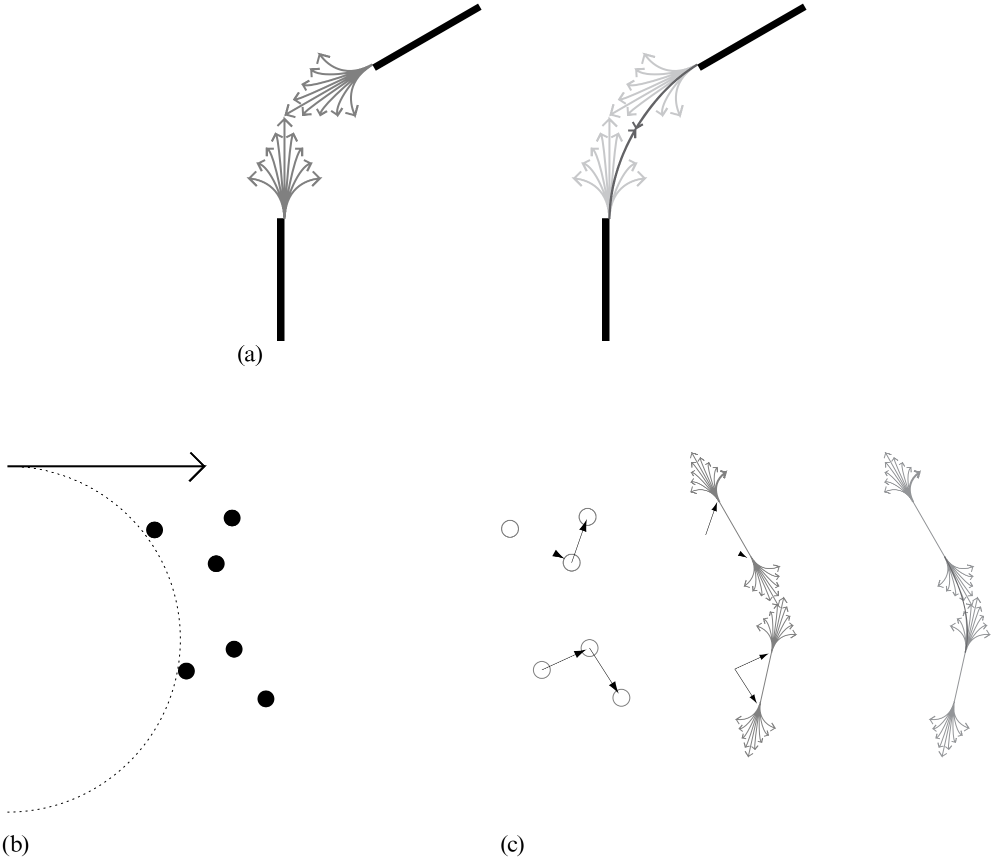

Figure 8. (a) An illustration of how extrapolation from two luminance-defined edges could lead to contour completion. (b) An illustration of a curved boundary moving over six elements. (c) The sequential change defines two sets of two motion vectors, which are shown as arrows. The two sets of motion vectors, when positioned with a common origin, define the local orientation of the moving edge. Contours extrapolated from the spatiotemporally defined edges may result in contour completion.

Completion may be seen as a process that works on individual edge fragments, and does not require any search for two relatable edges with discontinuities so that a specific contour may be interpolated between them. Instead, a simple, spatially limited, boundary-extension mechanism may suffice to link boundary fragments.

The boundary-completion mechanism that operates on static contours may also serve to complete spatiotemporally defined contours. Shipley and Kellman (1997) argued that the visual system integrates element changes over time by combining the motion signals defined by sequential changes. Furthermore, two motion signals, defined by at least three sequential changes in visibility, are sufficient to define the local orientation of an occluding edge. Each set of three changes may define a single local boundary segment. These boundary fragments must be combined into a whole form. We have proposed that at this stage these segments enter into the same contour interpolation process as occurs in displays with physically specified oriented edges. As an example, in figure 8b the leading edge of an opaque circle, indicated with a dotted line, sequentially occludes six elements. As illustrated in figure 8c, the sequential changes result in local motion signals that provide sufficient information to recover the orientation of the moving edge at a location along the circular boundary. Extrapolation away from each of the locally defined edges is illustrated with fans of radiating arrows. If the rules for linking edges are similar for static and moving edges, then an edge will be filled in where two extrapolated edges meet with the same orientation.

How might receiving elements interact with this fan of potential extrapolations? Perhaps extrapolated contours that meet similarly oriented luminance-defined contours are reinforced, just as extrapolated contours can support each other. The nature of this support remains unclear and an important direction for future research.

We do not present a detailed model at this point, because it is not yet clear how all the known phenomena of contour interpolation may be subsumed either in network interaction models, or in bipole models. Indeed, some merger of the two conceptions may be fruitful. Thus, the findings and observations here are not meant as disconfirmations of current accounts of boundary completion. They are meant to suggest that interpolation phenomena may be understood in part as resulting from an early visual process of contour *extrapolation*. Under some conditions, these extrapolations manifest themselves in perceptual phenomena not explainable by contour interpolation per se. The phenomena of amodal continuation and illusory-contour receiver elements both suggest the existence and importance of extrapolation processes.

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