Surface completion affected by luminance contrast polarity and common motion

Yong Su
Department of Basic Sciences, Pennsylvania College of Optometry at Salus University, Elkins Park, PA, USA, & Department of Psychological and Brain Sciences, University of Louisville, Louisville, KY, USA

Zijiang J. He
Department of Psychological and Brain Sciences, University of Louisville, Louisville, KY, USA

Teng Leng Ooi
Department of Basic Sciences, Pennsylvania College of Optometry at Salus University, Elkins Park, PA, USA

Our visual system ably integrates the visible parts of a partially occluded surface with the occluded parts (amodal surface completion), mainly by relying on the surface boundary contours of the image. Less known, is whether the visual system also utilizes surface feature information, such as luminance contrast polarity, for surface completion. We conducted three experiments to investigate this issue. Experiment 1 found that when visible segments of a partially occluded rectangle with the same luminance contrast polarity move behind an occluding surface, observers perceive the visible segments as part of the occluded rectangle moving cohesively behind the occluding surface. However, when the visible segments have opposite luminance contrast polarity, the global motion of the segments is barely perceived, suggesting a failure of amodal surface integration. Experiment 2 revealed that this same luminance contrast polarity constraint applies to amodal surface integration of a display without an explicit occluding surface image. Experiment 3 showed that both the shape and luminance contrast polarity of the visible segments of the partially occluded rectangle affect amodal surface completion. Together, these findings demonstrate that luminance contrast polarity, along with surface boundary contour, are important cues for amodal surface integration.

Keywords: amodal surface completion, boundary contour, contrast polarity, illusory contour, motion, surface representation

Citation: Su, Y., He, Z. J., & Ooi, T. L. (2010). Surface completion affected by luminance contrast polarity and common motion. *Journal of Vision, 10*(3):5, 1–14, http://journalofvision.org/10/3/5/, doi:10.1167/10.3.5.

Introduction

Surface occlusion that occurs frequently in the external visual scene presents a special challenge to the surface representation process. A partially occluded surface does not have its occluded parts imaged on the retina, while the same surface's non-occluded parts are imaged on the retina as separated image patches. Thus, to represent a partially occluded surface, the visual system has to fill-in the occluded parts of the surface and piece them together with the separated, non-occluded parts of the surface (amodal surface completion). Broadly speaking, the visual system can use two classes of cues to construct the occluded surface. The first is related to the surface relationship *between the occluding and occluded surfaces,* e.g., the various contour junctions, relative motion parallax, relative binocular disparity, etc. The second class of cues is related to the surface relationship *between the non-occluded parts of the surface,* which includes their geometric relationship and surface feature similarity. The geometric relationship pertains to, for example, whether the visible (non-occluded) surface patches have similar surface curvature, or whether they are aligned and could potentially form a smooth continuous surface (e.g., Fantoni, Bertamini, & Gerbino, 2005; Kanizsa, 1979; Kellman, Garrigan, & Shipley, 2005; Kellman & Shipley, 1991; Nakayama & Shimojo, 1990; Nakayama, Shimojo, & Silverman, 1989; Sekuler, 1994; Tse, 1999). The surface feature cue is concerned with whether the non-occluded surface patches have similar surface feature properties such as texture, color, luminance, etc. (He & Ooi, 1998; Kanizsa, 1979; Koffka, 1935; Spehar, 2000; Spehar & Clifford, 2003; Yin, Kellman, & Shipley, 1997, 2000). Whereas much research has shown elements with similar surface feature properties tend to group together, few studies have demonstrated this Gestalt principle (similarity) applies to amodal surface integration (e.g., Yin et al., 1997, 2000). Of the few such studies, Yin et al. (1997) used a display where an opaque rectangle occludes the middle section of a curved bar. A small disc was added onto the rectangular surface and located along the invisible path of the occluded curved bar. The authors found that when the surface feature (texture and color) of the disc was similar

doi: 10.1167/10.3.5 Received July 7, 2009; published March 24, 2010 ISSN 1534-7362 © ARVO

to the features of the visible parts of the partially occluded bar, observers were more likely to perceive the disc as an aperture (hole). In contrast, their observers had a bias to perceive the disc as a figure (spot) on the rectangular surface when it had different surface features from the partially occluded bar. Since the observed completion was largely based on surface features, and because the boundary contour of the disc could not integrate with the boundary contour of the occluded bar, Yin et al. coined this "surface completion". Yet, the general lack of empirical evidence of surface features contributing to surface contour completion has led most theories of surface representation to assign a modest role to surface features in the surface completion process (Grossberg & Mingolla, 1985; Kellman & Shipley, 1991). Given this, a goal of our paper is to investigate whether luminance contrast polarity, a fundamental surface feature property, plays a significant role in representing a partially occluded surface.

Let us consider Figure 1a where the inner and outer rectangular spokes along the same radial direction have the same luminance contrast polarity (He & Ooi, 1998).

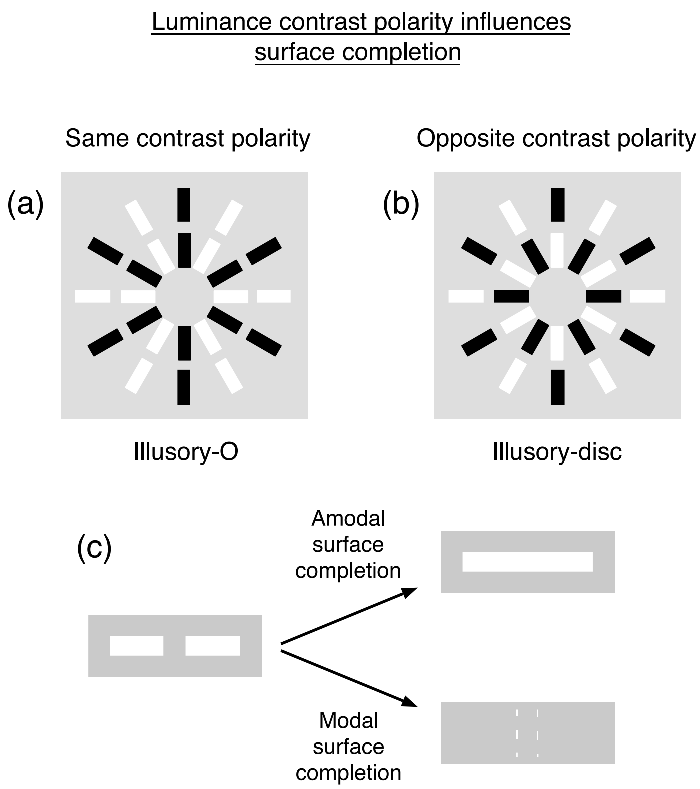

Figure 1. The effect of luminance contrast polarity on surface completion. Adjacent rectangular spokes along the same radial direction are rendered with either (a) the same or (b) opposite luminance contrast polarity. This leads to the perception of either (a) an illusory-O or (b) illusory-disc. (c) We hypothesize that the L-junctions (corners) of adjacent spokes with the same luminance contrast polarity are treated as implicit T-junctions, resulting in amodal and modal surface completion (illusory-O).

By fixating at the center of the display, one perceives an illusory ring (illusory-O) occluding one longer rectangular spoke. Even though the perceived longer rectangular spoke is made up of two separated shorter spokes, it is as if the two separated spokes are now joined beneath the illusory-O occluder. To account for the illusory-O perception, He and Ooi (1998) proposed the visual system amodally completes the aligned inner and outer spokes as a single, long rectangle, and modally constructs an illusory-O (ring surface) to occlude the long rectangle. The basic concept is illustrated in Figure 1c with a pair of rectangular spokes in the horizontal radial direction. The corners of the rectangular segments (L-junctions) separated by the gap are now treated as implicit T-junctions. T-junction is a monocular cue for amodal surface completion (Anderson & Julesz, 1995; Guzman, 1969; Nakayama, He, & Shimojo, 1995; Rubin, 2001; Stoner & Albright, 1996). As such, the two smaller white rectangles are amodally completed as one longer rectangle, with a modal surface (illusory-O) perceptually created to occlude the longer rectangular surface. To reveal the constraint of same contrast polarity, He and Ooi (1998) designed Figure 1b where the inner and outer rectangular spokes along the same radial direction have opposite luminance contrast polarity. They found having an opposite luminance contrast polarity prevents the formation of illusory-O; instead an illusory disc (not ring) is seen.

Arguably, He and Ooi's (1998) findings only provided an indirect evidence for the role of luminance contrast polarity in amodal surface completion. This is because they only measured the perceived illusory-O (modal surface), and not the perceived amodal surface completion (occluded surface) between the inner and outer rectangular spokes.

To directly examine the role of luminance contrast polarity in amodal surface completion, we explore the perception of object motion behind an occluder. Figure 2a schematically depicts a gray rectangle moving horizontally behind two black vertical rectangles (occluders). The two vertical occluders essentially divide the gray rectangle into three smaller rectangular segments: two outer rectangles and one middle rectangle. Further, owing to the absence of texture information within the rectangular segments, the local motion signals are only found at the vertical edges/terminals of the two outer rectangles (arrows in Figure 2a) and not in the middle rectangle. How does the visual system obtain global motion from these two local motion signals, which are ambiguous? To derive global motion from local motion information at the surface's edges, the visual system often utilizes the spatial configuration cues (Adelson & Movshon, 1984; Duncan, Albright, & Stoner, 2000; He & Nakayama, 1994; He & Ooi, 1999; Lorenceau & Shiffrar, 1992; Nakayama & Silverman, 1985; Shimojo, Silverman, & Nakayama, 1989; Stoner & Albright, 1996; Watamaniuk & McKee, 1995; Watanabe, 1997). An important spatial configuration cue is derived from the assignment of border

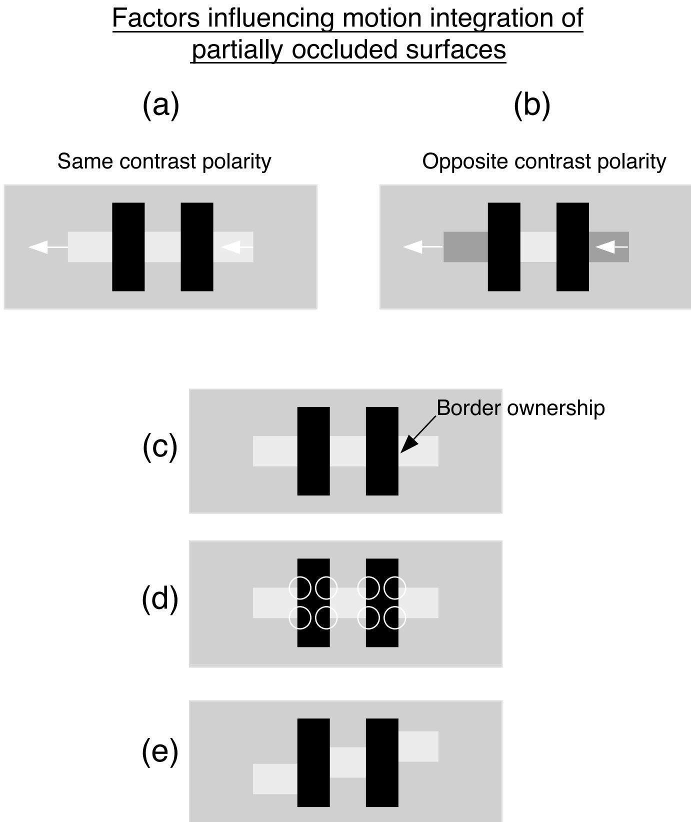

Figure 2. (a) Three horizontal rectangular segments with the same luminance contrast polarity are seen as belonging to the same object (one longer horizontal rectangle) moving leftward in global motion. (b) The inner horizontal rectangular segment has an opposite luminance contrast polarity compared to the outer rectangular segments, leading to a failure in surface integration. The left outer rectangular segment is seen as expanding while the right outer rectangle compresses. (c–e) Analysis of the factors involved in surface completion. See text for details.

ownership to the surface's edge (Shimojo et al., 1989). Figure 2c analyzes of the motion condition in Figure 2a. Notice the right outer rectangular segment has a right edge that carries the local, leftward motion signal, and a left edge that is shared with the vertical black rectangle. If the left edge is deemed to own the border, a stationary or no motion signal is attached to the left terminal edge of the right rectangular segment. This leads the visual system to interpret the rectangular segment as being compressed leftward while its left edge remains stationary. However, if the border ownership is assigned to the black vertical rectangle and not the left edge of the right outer rectangle, the visual system may not necessarily interpret the left edge of the right rectangle as stationary, but instead as part of a longer rectangle moving behind the black vertical rectangle that occludes it. Thus, depending on how the visual system integrates the three rectangular segments (given the available visual cues), there are two possible perceptual interpretations of the motion display in Figure 2a. We further consider this issue below.

As mentioned, the visual system can use two classes of cues to represent overlapping surfaces. One, which exists *between the occluding and occluded surfaces* is the T-junction cue. The circles drawn onto Figure 2d indicate the T-junctions formed between the gray rectangular segments and black vertical rectangles. The particular configuration of the T-junctions leads the visual system to assign the border ownership to the black vertical rectangles and not the gray rectangular segments. Then the alignment between the left and right pairs of T-junctions (alignment is a factor in the second class of cues related to the surface features *between the non-occluded parts of the surface*) facilitates amodal surface integration between the middle and two outer rectangles (Figures 2d vs. 2e) (e.g., He & Ooi, 1998, 1999; Kellman & Shipley, 1991; Rubin, 2001). Another factor in the second class of cues for amodal surface completion is whether the aligned T-junction stems (horizontal edges of the separated rectangular segments) have the same contrast polarity (He & Ooi, 1998). For the motion display in Figure 2a, all three rectangular segments are lighter than the background, and thus all the aligned junction stems have the same positive luminance contrast polarity. But for the motion display in Figure 2b, the contrast polarity of the middle rectangular segment (positive) is opposite to that of the two outer rectangular segments (negative). It has been shown that motion signals with positive and negative contrast polarity are processed separately in the early motion pathway (e.g., Croner & Albright, 1997; Del Viva, Gori, & Burr, 2006; van der Smagt, Breij, & van de Grind, 2000; van der Smagt & van de Grind, 1999; Wehrhahn & Rapf, 1992). Thus, if the visual system has a preference to group or integrate separated segments with the same contrast polarity into one common amodal surface, the observer is less likely to perceive all three rectangular segments with opposite contrast polarity in Figure 2b as one longer gray rectangle occluded by the black vertical rectangles. For Figure 2a where surface completion is possible, we can predict motion signals from the two outer rectangles propagate to the middle stationary rectangle, leading to one perceiving a strong global motion of the long rectangle moving leftward. But for the display in Figure 2b, one only perceives independent motion of the terminals of the two outer rectangular elements, which results in a leftward expansion of the left rectangle and a synchronous compression of the right rectangle, while the middle rectangle remains stationary. Experiment 1 tested these predictions using the displays in Figure 5.

Experiment 2 was also motivated by the illusory-O study (He & Ooi, 1998). We examined if the same contrast polarity constraint applies to motion displays with illusory occluding surfaces (Figure 3). In contrast to Figure 2a, the motion display in Figure 3a does not have the two black vertical rectangles to physically serve as the occluders. Local, leftward motion signals are now rendered to the edges/terminals of the two gaps (arrows in Figure 3a). From the illusory-O perception, we can predict the visual

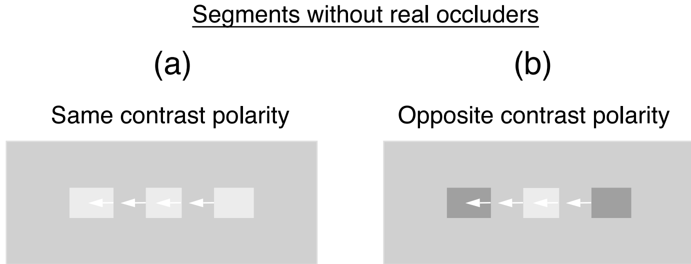

Figure 3. Separated rectangular segments with (a) same luminance contrast polarity and (b) opposite luminance contrast polarity. No real occluder exists between separated segments. The white arrows indicate the terminal edges that are rendered with local motion signals.

system amodally completes the outer gray rectangular segments with the middle rectangular segment into a single longer horizontal rectangle (Figure 3a). Further, because the left edge of the left outer rectangle and right edge of the right outer rectangle do not carry local motion signals, the amodally completed rectangle is not perceived as moving. Meanwhile, the gaps are now modally completed as illusory vertical occluders, and they move leftward as a unit (since the illusory rectangular edges demarcating the gaps carry the local motion signals). But for the motion display in Figure 3b, amodal surface completion does not occur because the middle and the two outer rectangular segments have opposite luminance contrast polarity. All the terminal edges of the rectangular segments at the gaps now own the borders and thus carry the local motion signals. Consequently, one perceives only the middle rectangle moving leftward as the left outer rectangle compresses and right outer rectangle expands leftward. These predictions are confirmed in Experiment 2 using the displays in Figure 8.

Experiment 3 extended Experiment 2's observations by manipulating the terminal shape of the rectangular segments adjacent to the gaps (Figure 10b). We found when arrowhead-shaped terminals were used, amodal surface completion between the outer and middle rectangular segments became weaker and observers were less likely to see them as an integrated unit.

The studies presented in this paper have been previously reported in an abstract form (Su, Ooi, & He, 2004).

Experiment 1

Figures 4a and 4b illustrate two motion stimuli modified, respectively, from Figures 2a and 2b. In both displays, the black diamond frame (real, physical occluder) and the gray X-shaped elements within the diamond frame are stationary while the outer oblique rectangles carry the local motion signals depicted by the arrows. In Figure 4a, the stationary X-shaped elements and the outer oblique rectangles have the same luminance contrast polarity and they are expected to be amodally completed behind the black diamond frame. It is predicted the observer will perceive the display as two longer oblique rectangles sliding over one another behind the black diamond frame (arrows) (global motion). In Figure 4b, the outer oblique rectangles are darker than the background while the X-shaped elements (inner oblique rectangles) are lighter than the background. This sets up a condition where the outer rectangles have an opposite contrast polarity relative to the background compared to the inner rectangles. According to the same contrast polarity constraint, no amodal surface completion will occur between the inner and outer rectangles. This leads to the prediction the inner rectangles within the black diamond frame will be seen as stationary while the outer rectangles along each oblique axis compress and expand in synchrony (arrows), i.e., no motion integration.

To test these predictions, we used the four types of displays shown in Figure 5. Figures 5a and 5b are the same as those in Figure 4, while Figures 5c and 5d have the stimulus background luminance increased so that both the outer and inner rectangles have the same negative contrast polarity. We predict all displays except that in Figure 5b will induce the perception of sliding motion

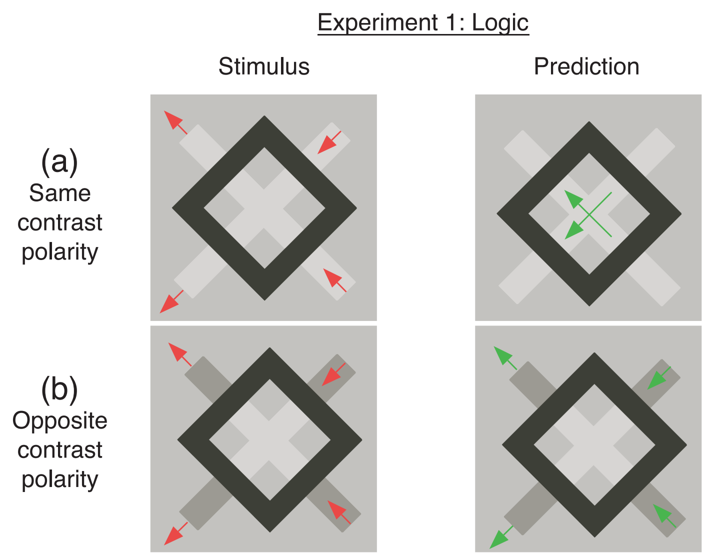

Figure 4. The logic of Experiment 1. The terminal edges of stimuli (a) and (b) are rendered with local motion signals (arrows). All aspects of both stimuli are the same except for the luminance of the outer rectangular segments of stimulus (b), which leads to them having an opposite luminance contrast polarity relative to the inner rectangular segments. It is predicted that the inner rectangles in stimulus (a) with the same luminance contrast polarity are seen as sliding over each other (arrows) as they move together with the outer rectangles (global motion). In contrast, the inner rectangles in stimulus (b) with the opposite luminance contrast polarity are seen as stationary while the outer rectangles expand and compress.

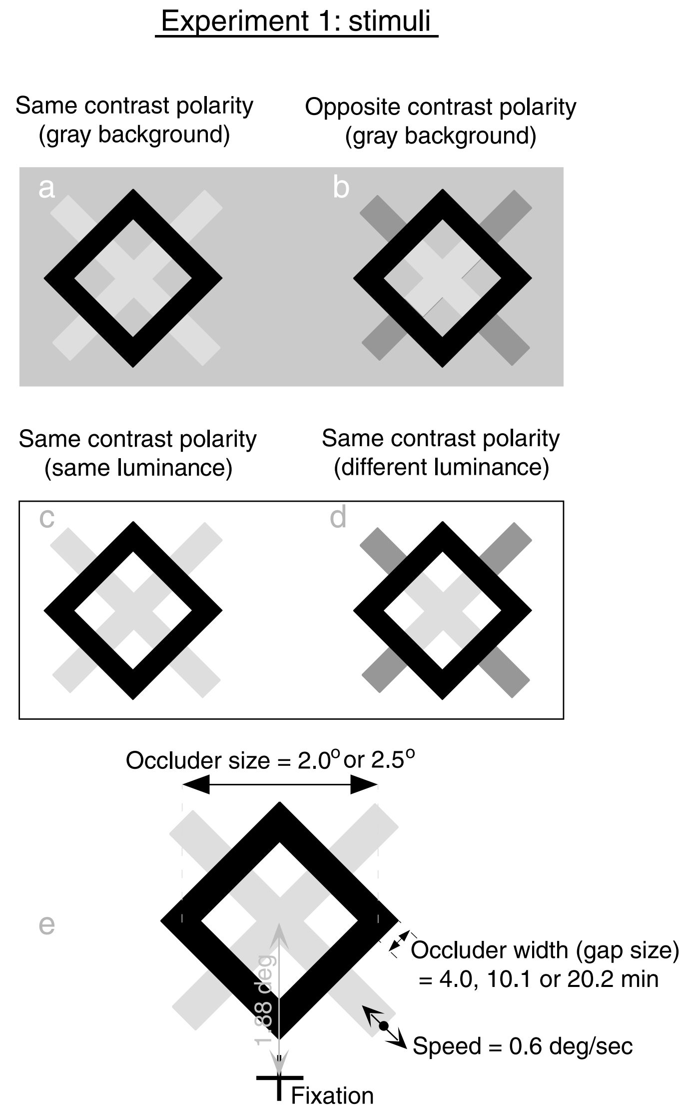

Figure 5. The stimuli used in Experiment 1 (not drawn to scale). Stimuli (a) and (b) are the same as the ones in Figure 4. Stimuli (c) and (d) are similar to (a) and (b) except for the background luminance. The general dimensions of the stimulus are specified in (e).

(global motion). It is noteworthy that in Figure 5d, even though the outer and inner rectangles have different luminance levels, they have the same (negative) contrast polarity relative to the background. Thus, if luminance contrast polarity (sign), rather than luminance level itself, is critical for amodal surface completion between the rectangular elements, amodal surface completion is expected to occur in Figure 5d as in Figure 5c. Figure 5e depicts the stimulus dimensions used in our experiment. We used two different sizes of the occluding diamond frame and three different frame thickness.

At this juncture, one might wonder why our experiment measured the perceived global motion patterns rather than use the task of subjective rating to subjectively rate the perceived amodal surface of the rectangle in Figure 1a. The latter task has frequently been used to measure the perceived illusory contours, such as in the study of the illusory-O perception by He and Ooi (1998). The main reason is that the representation of an occluded surface is invisible even as it produces a perceptual impression of being occluded. Thus, observers cannot reliably report this impression, as it could be confused with the impression of perceptual grouping between the visible rectangular segments that occurs even when there is no amodal surface integration between them. This is in contrast to the representation of an illusory contour (modal integration) whose image properties, such as contour sharpness, is visible and can be reliably used in a perceptual judgment task. Therefore, one has to use an indirect psychophysical method to measure the perceptual quality that is a consequence of amodal surface integration.

Methods

Stimuli

A Power Mac G4 computer running MATLAB and Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) generated and presented the visual stimuli on a 17-inch flat-screen CRT monitor. The resolution of the monitor was set to 1024 × 768 pixels at a refresh rate of 100 Hz. A chin- and headrest was used to stabilize the seated observer from a viewing distance of 75 cm.

The stimulus (Figure 5) comprised two oblique bars (orientation = ±45°, length = 2.5°, width = 0.33°) arranged in an X-shape formation and a black diamond frame (0.1 cd/m^2) that acted as the occluder. The occluder effectively divided each oblique bar into three rectangular segments: two outer rectangles and one inner rectangle. The outermost edges of the outer rectangles were rendered with a terminal velocity of 0.6°/sec (along its motion direction), with a maximum displacement of 0.57°. The entire stimulus was presented above a black fixation target (0.4° × 0.4°). The distance of the fixation target from the center of the stimulus was 1.88°.

Two aspects of the diamond frame occluder were varied (Figure 5e). The first was the occluder width (4.0, 10.1, or 20.2 min), which effectively varied the gap size of the stimulus. The second was the overall size of the occluder, being either 2.0° or 2.5° (as measured along the axis of the diamond).

To manipulate the contrast polarity of the inner and outer rectangles with respect to the background, we fixed the luminance of the inner rectangles at a constant level (21.6 cd/m^2) while varied the luminance levels of both the outer rectangles (4.9 or 21.6 cd/m^2) and the homogeneous background (12.5 or 61.9 cd/m^2). With such an arrangement, the inner and outer rectangles had an opposite contrast polarity relative to the background only when they were presented against the darker background (Figure 5b, opposite contrast polarity condition). When the brighter background was employed, the inner and outer rectangles had the same contrast polarity with respect to the background. Therefore, the influence of contrast polarity can be distinguished from that of luminance.

Observers

Two authors and four naïve observers participated. All observers had normal or corrected-to-normal visual acuity and a stereoscopic resolution of 40 arcsec or better. Informed consent was obtained from the naïve observers before commencing the experiment.

Procedures

To begin a trial, the observer first stabilized his eye fixation at the fixation target and then pressed the space bar of the computer keyboard to present the stimulus. He was instructed to maintain good eye alignment with the fixation target throughout the entire 1.5-sec stimulus presentation duration. The observer responded to seeing either one of two percepts. The first is, of two partially occluded oblique bars sliding over each other back and forth (global motion when motion integration occurred; see the prediction in Figure 4a). The second is, of the four outer rectangles expanding and contracting while the inner rectangles remained stationary (when motion integration failed; see the prediction in Figure 4b). To report the percept, the observer pressed the left or right arrow key on the keyboard, respectively, for the first or second percept.

Each test block had 96 trials, which included 4 repetitions of the 24 stimulus combinations (2 luminance levels of the outer rectangles × 2 background luminance levels × 3 gap sizes × 2 occluder sizes). For each observer, six such blocks were conducted during the test session. The first two blocks were treated as familiarization blocks, and only data from the last four blocks (i.e., 16 trials for each stimulus combination) were used for analysis. In all, three same luminance contrast polarity conditions (see Movies 5a, 5c, and 5d) and one opposite luminance contrast polarity condition (Movie 5b) were tested.

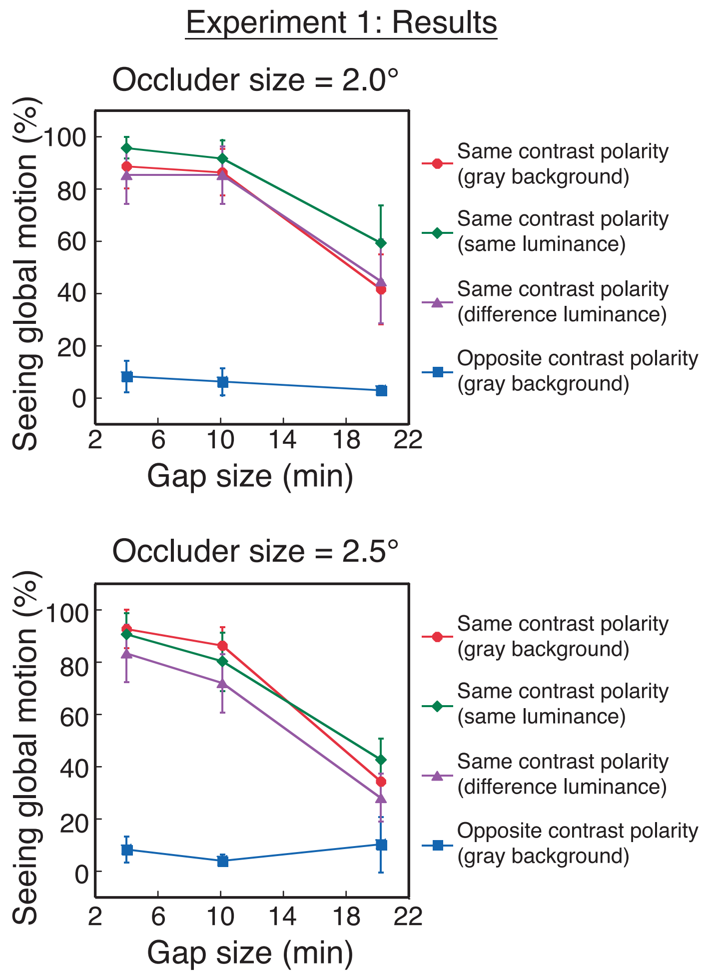

Figure 6. Results of Experiment 1 for the stimuli with the small (upper graph) and large (lower graph) occluder sizes. Overall, motion integration (global motion) occurs in the conditions with the same luminance contrast polarity. But little global motion is perceived in the opposite luminance contrast polarity conditions.

Results

Figure 6 illustrates the average percentages of perceiving motion integration as a function of gap sizes for the small (upper graph) and large occluder sizes (lower graph). Clearly, the percentages of perceiving integrated motion are very low (almost zero) in the opposite contrast polarity condition (Figure 5b), unlike those in the same contrast polarity conditions. The *p*-values of one-sample *t*-test for all data points in the opposite contrast polarity condition range between 0.076 and 0.363, and overall, the data points are significantly lower than those in the three same contrast polarity conditions (Figures 5a, 5c, and 5d) (ANOVA with contrast analysis: $F_{1,\ 5} = 67.427$, $p < 0.001$). Furthermore, the data of the two same contrast polarity conditions with the lighter background (Figures 5c and 5d) are similar to the data of the same contrast polarity condition with the darker background (Figure 5a) (ANOVA with contrast analysis: $F_{1,\ 5} = 1.194$, $p = 0.324$; $F_{1,\ 5} = 3.324$, $p = 0.128$). This suggests neither the luminance difference between the elements (Figures 5c vs. 5d) nor the luminance of the background (Figures 5a vs. 5c) can account for the poor motion integration of the opposite contrast polarity condition (Figure 5b). Thus, the results support the prediction the visual system can only amodally complete elements with the same luminance contrast polarity to achieve a global motion percept (Figure 4).

The gap size factor also has a significant main effect on motion integration [$F_{1.037,\ 5.187} = 20.903$, $p = 0.005$

(with Greenhouse–Geisser correction); ANOVA with repeated measures] and an interaction with contrast polarity [$F_{2.216,\ 11.081} = 12.971$, $p = 0.001$ (with Greenhouse–Geisser correction); ANOVA with repeated measures]. As described, motion integration is almost absent in the opposite contrast polarity condition regardless of the gap size. However, when the inner and outer rectangles of the stimulus has the same contrast polarity, increasing the gap size results in significantly less motion integration. Yet changing the occluder size does not significantly affect motion integration ($F_{1,\ 5} = 3.644$, $p = 0.115$; ANOVA with repeated measures). One possibility is the two occluder sizes were not sufficiently large to reveal an effect on amodal surface completion.

Experiment 2

To investigate if the same contrast polarity constraint applies to the perception of illusory surfaces and global motion, we first considered the two displays in Figure 7. For the display with the same contrast polarity (Figure 7a, left), the aligned rectangular elements separated by the two gaps along the same oblique axis amodally complete as a single longer rectangle. Then, further facilitated by the parallel edges of the gap (see Experiment 3 for detailed explanation), (modal) illusory surface patches are formed at each gap (as described in Figure 3a). Consequently all four illusory surface patches are integrated into an illusory diamond frame that moves rightward (global motion) over the amodally completed rectangles (Figure 7a, right). Meanwhile, the two amodally completed rectangles are perceived as stationary. However, when the outer rectangular elements are darker than the background (Figure 7b, left), they have opposite luminance contrast polarity relative to the background compared to that of the inner rectangular elements. Thus, according to the same contrast polarity constraint, the visual system can no longer amodally complete the rectangular elements, nor create an illusory diamond frame in front. Without the illusory diamond frame formation, one sees the inner rectangles sliding over each other, instead of remaining stationary (Figure 7b, right).

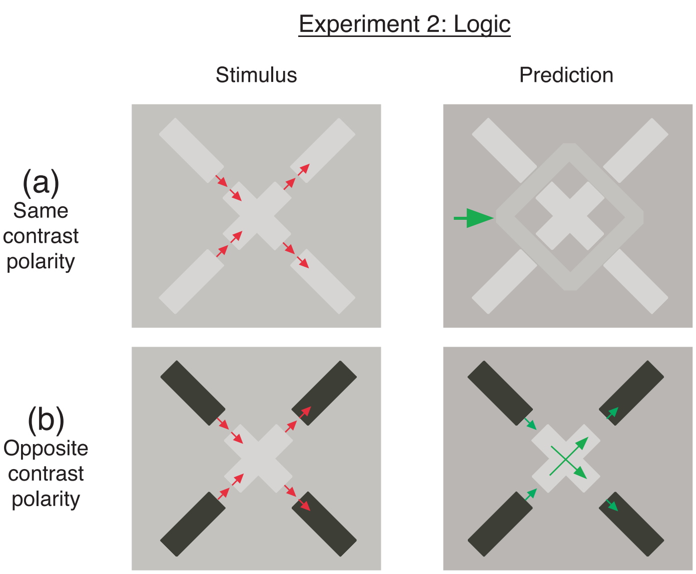

Figure 7. The logic of Experiment 2. The terminal edges of stimuli (a) and (b) are rendered with local motion signals (arrows). All aspects of both stimuli are the same except for the luminance of the outer rectangular segments of stimulus (b), which leads to them having an opposite luminance contrast polarity relative to the inner rectangular segments. It is predicted that the inner rectangles in stimulus (a) with the same luminance contrast polarity are seen as stationary, and an illusory diamond frame is seen as moving laterally (rightward arrow). In contrast, the inner rectangles in stimulus (b) with the opposite luminance contrast polarity are seen as sliding over each other (arrows), with their movements causing the outer rectangles to either compress or expand. During the experiment, we instructed the observers to report seeing either the inner rectangles as moving (no motion integration) or stationary (motion integration leading to global motion of the illusory diamond frame).

We tested the predictions above using the four types of displays in Figure 8. Figures 8a and 8b are the same as those in Figure 7, while Figures 8c and 8d have a lighter background that causes all the rectangular elements to have the same (negative) contrast polarity relative to the background. Similar to Experiment 1 above, we varied the gap sizes of the display. Also, we varied the distance between each pair of opposing gaps (inter-gap distance, Figure 8e), which is similar to changing the overall size of the occluder in Experiment 1.

Methods

Stimuli

The general design of the stimulus (Figure 8) was similar to that used in Experiment 1. That is, the X-shaped stimulus with an overall size of roughly 3° × 3°, was formed by two intersecting oblique bars (orientation = ±45°, length = 3.91°, width = 0.33°). Two gaps were inserted into each oblique bar, essentially breaking the oblique bar into three rectangular segments. The spaces of the gaps were filled with the same gray level as the background. The boundaries of each gap, i.e., the inner edge of the outer rectangle and the outer edge of the adjacent inner rectangle, were rendered with back-and-forth motion along the long axis of the rectangle (0.6°/sec, maximum displacement = 0.57°). Thus, an expansion of one outer rectangle was synchronized with a contraction of the adjacent inner rectangle along the same direction, essentially, causing the gap between the rectangles to move along.

Considered in its entirety, and at any given moment, all four gaps of the X-shaped stimulus would have the same

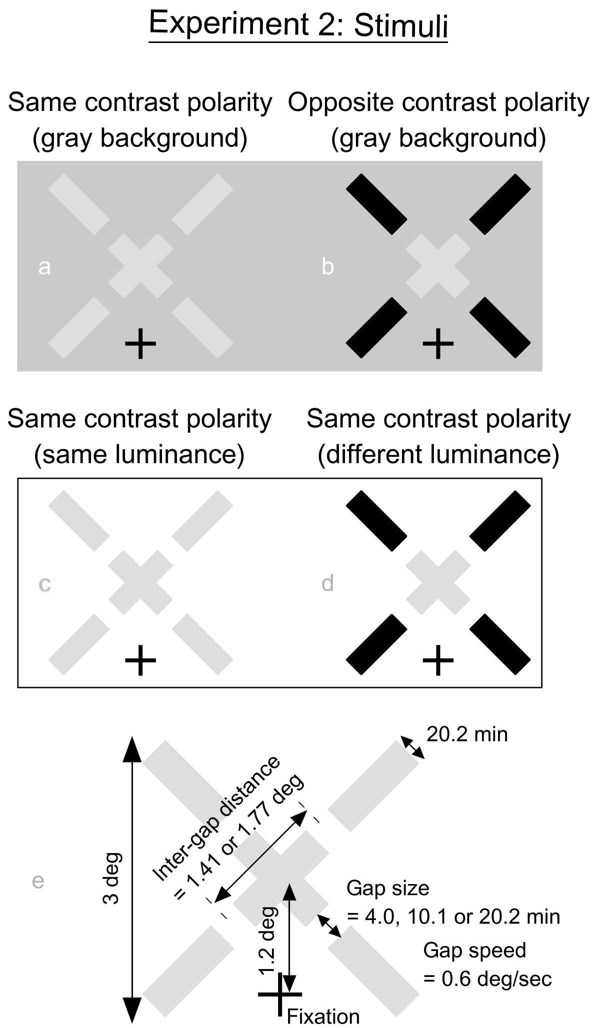

Figure 8. The stimuli used in Experiment 2 (not drawn to scale). Stimuli (a) and (b) are the same as the ones in Figure 7. Stimuli (c) and (d) are similar to (a) and (b) except for the background luminance. The general dimensions of the stimulus are specified in (e).

horizontal motion component so that it was possible to conceive them as parts of an illusory diamond occluder translating horizontally. To stabilize eye alignment, a 0.4° × 0.4° black fixation target was located 1.2° below the center of the stimulus during the entire stimulus presentation of a test trial.

As in Experiment 1, luminance contrast polarity was manipulated by changing the luminance of the background (12.5 or 61.9 cd/m^2) and/or that of the outer rectangles (4.9 or 21.6 cd/m^2), while keeping that of the inner rectangles constant (21.6 cd/m^2). Thus, we have three same luminance contrast polarity conditions (Figures 8a, 8c, and 8d; see Movies 8a, 8c, and 8d) and one opposite luminance contrast polarity condition (Figure 8b; Movie 8b). The width of the gap size was also varied (4.0, 10.1, or 20.2 min), as was the distance between each pair of opposing gaps (inter-gap distance). The two inter-gap distances used were 1.41° and 1.77°.

Observers

The same observers (n = 6) who participated in Experiment 1 participated in this experiment.

Procedures

The same test procedure as in Experiment 1 was adopted. The observers' task was to report their percepts of the stimuli, which were either: (i) two inner rectangles remaining stationary or (ii) two inner rectangles sliding over each other. The observers pressed the left arrow key of the keyboard for percept (i) and the right arrow key for percept (ii).

Each observer was tested in an experimental session comprising six test blocks. Each block had 96 trials, i.e., 4 repetitions of 24 stimulus combinations (2 luminance levels of the outer rectangles × 2 background luminance levels × 3 gap sizes × 2 inter-gap distances). The first two blocks of trials were taken as familiarization trials. Data from the last four blocks (i.e., 16 trials for each condition combination) were used for analysis.

Results

The average data are plotted in Figure 9. The percentages of perceiving global motion (motion integration) in the opposite contrast polarity condition are only slightly above zero (one-sample t-test for every combination of gap size and occluder size: $p > 0.175$), which are significantly lower than those in the three same contrast polarity conditions ($F_{1,\ 5} = 28.836$, $p = 0.003$; ANOVA with contrast analysis). There is also an interaction effect between contrast polarity and gap size [$F_{2.607,\ 13.035} = 6.031$, $p = 0.010$ (with Greenhouse–Geisser correction); ANOVA with repeated measures]. This finding confirms the same contrast polarity constraint applies both to amodal surface completion between separated elements and modal surface completion (illusory surface formation).

Additionally, for all the three same contrast polarity conditions, motion integration decays with increasing gap size [$F_{1.116,\ 5.578} = 11.998$, $p = 0.014$ (with Greenhouse–Geisser correction); ANOVA with repeated measures]. As in Experiment 1, there is no significant effect of inter-gap distance on motion perception ($F_{1,\ 5} = 0.033$, $p = 0.863$; ANOVA with repeated measures).

We also noticed when the illusory diamond shape is perceived as a unique moving object, the perceptual impression of the diamond shape is stronger than when the display is not rendered with local motion signals.

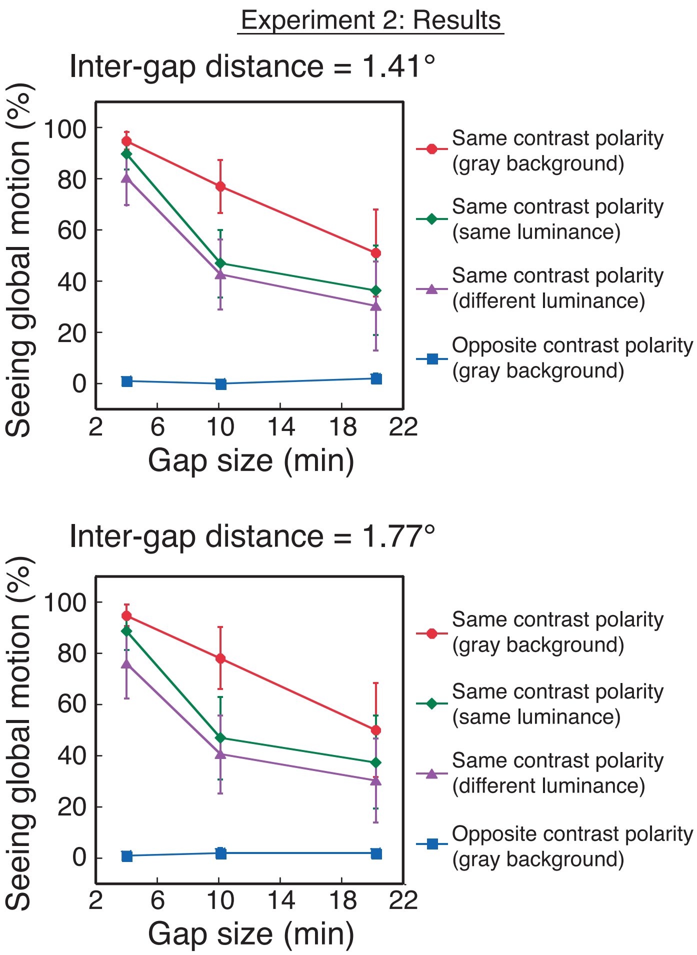

Figure 9. Results of Experiment 2 for the stimuli with the small (upper graph) and large (lower graph) inter-gap distances. Overall, motion integration (global motion of the illusory diamond frame) occurs in the conditions with the same luminance contrast polarity. But little motion integration is perceived in the opposite luminance contrast polarity conditions.

This suggests a common motion signal facilitates the integration of the illusory elements to become a single illusory figure (Anderson & Barth, 1999; Kellman & Cohen, 1984; Yonas, Craton, & Thompson, 1987).

Experiment 3

The goal of this experiment is to further test the explanation that in Experiment 2, surface completion plays a critical role in determining the global motion percept of the rectangles. We changed the terminal shape of the rectangular elements from flat (Figures 10a and 10c) to arrowhead (Figures 10b and 10d), which is an invalid shape for amodal surface completion between two separated elements. Having parallel terminal edges between the two juxtaposed rectangular elements could facilitate amodal surface integration (Figures 10a and 10c). This is because the visual system has a tendency to treat parallel edges as opposite sides of an object/surface (Albert, 1993; Rock, 1983). This tendency leads to a bias for forming an illusory surface patch that owns the two parallel borders/edges. Furthermore, this illusory surface patch is interpreted as occluding the inner and outer rectangles (Figure 10f), causing both the rectangles to yield their borders to the occluding illusory surface patch, which facilitates their amodal surface integration. In contrast, in the shape-invalid display where the terminal shape of the juxtaposed rectangles is arrowhead (convex shape) rather than flat (parallel), amodal surface completion between the juxtaposed rectangles is less likely to occur. Moreover, the illusory surface that would be created would have an odd

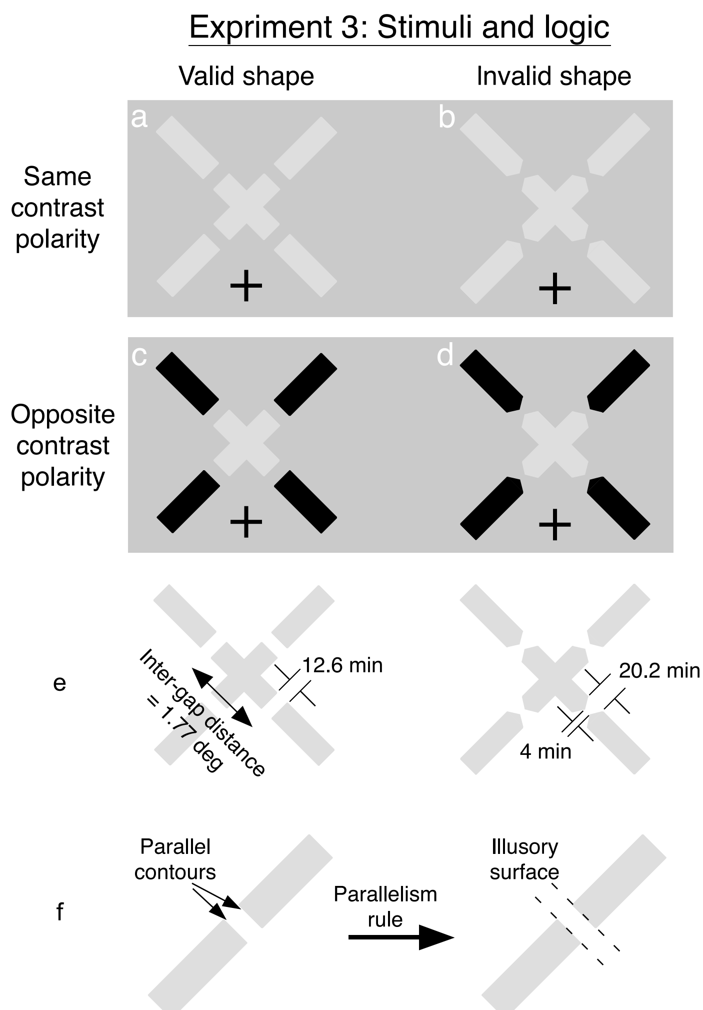

Figure 10. (a–d) The stimuli used in Experiment 3 (not drawn to scale). Luminance contrast polarity (a, b vs. c, d) and terminal shape (a, c vs. b, d) were varied. The stimuli (a, c) with the valid terminal shape have parallel/flat edges, while the stimuli (b, d) with the invalid shape have arrowhead edges. (e) The general stimulus dimensions of the valid and invalid shaped stimuli. (f) A depiction of the "parallelism rule," which allows the formation of an illusory surface when there exists a gap with parallel edges.

shape. Accordingly, for the four displays in Figure 10, we can predict little or no perception of moving illusory diamond frame will be seen in Figure 10b, unlike in Figure 10a, even though the elements have the same contrast polarity. We can also predict no moving illusory diamond frame will be observed for the displays in Figures 10c and 10d due to their having opposite contrast polarity.

Methods

Stimuli

Two terminal shape conditions (flat vs. arrowhead) were tested (Figure 10). The stimuli for the flat-terminal condition were the same as a subset of the stimuli used in Experiment 2. Specifically, only the larger stimuli with an inter-gap distance of 1.77°, a gap size of 12.6 min and displayed against the darker background (12.5 cd/m^2) were employed. The stimuli for the arrowhead-terminal condition were modified from those in the flat-terminal condition by "sharpening" the terminal endings. Doing so altered the shape of the gap from parallel to arrowhead. The width of the arrowhead gap at its narrowest location in the middle was 4 min, and at its widest locations on the sides was 20.2 min. These dimensions were chosen so that the average width of the arrowhead gap was similar to that of the parallel gap (12.6 min).

Observers

The six observers who participated in the previous two experiments participated in this experiment.

Procedures

The same test procedure and task as in Experiment 2 were adopted, except that only four stimulus combinations were tested (2 luminance levels of outer rectangle × 2 terminal shapes; see Movie 10b vs. Movie 8a and Movie 10d vs. Movie 8b). A test block comprised 64 trials (i.e., 16 repetitions per stimulus combination). Each observer was tested over four blocks of trials, with the first two blocks being taken as familiarization blocks. Data collected from the last two blocks were used for analysis (i.e., 32 trials per stimulus combination).

Results

Figure 11 depicts the average results. As in the previous experiments, the percentages of perceiving integrated motion are higher in the same contrast polarity condition than in the opposite contrast polarity condition ($F_{1,\ 5}$ = 18.187, p = 0.008; ANOVA with repeated measures). In addition, when the juxtaposed rectangles had the arrowhead terminals (invalid shape), observers saw less motion integration compared to when they had flat (parallel) terminals (valid shape) ($F_{1,\ 5}$ = 6.820, p = 0.048; ANOVA with repeated measures). This confirms the prediction that the shape factor that affects surface completion between separated elements also influences the global motion perception.

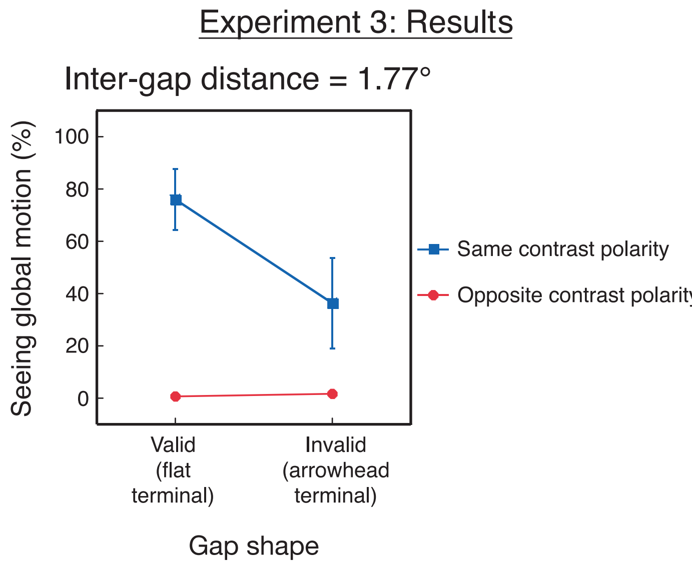

Figure 11. Results of Experiment 3. Overall, motion integration (global motion of the illusory diamond frame) occurs predominantly in the condition with the same luminance contrast polarity and valid terminal shape (parallel/flat edge). As expected, little motion integration is perceived in the opposite luminance contrast polarity condition regardless of terminal shape.

General discussion

In summary, we first revealed elements with the same luminance contrast polarity but physically separated by a real occluding surface are amodally integrated and perceived as moving together (global motion). The global motion percept is not experienced when the separated elements have opposite luminance contrast polarity. Second, we showed even without a real occluding surface image, separated elements with the same luminance contrast polarity are amodally integrated and an illusory occluding (modal) surface is perceived along with the integrated motion (global motion). This finding extends the observation of the illusory-O display of He and Ooi (1998). Third, we found an invalid terminal shape degrades both surface integration and global motion perception. In all, these experiments suggest motion signals can propagate along the visible as well as the invisible parts (amodal) of a partially occluded surface, leading to the partially occluded surface being perceived as moving together as a single entity.

We mentioned the illusory-O display (Figure 1) provides a clear demonstration luminance contrast polarity plays a critical role in surface completion. This led He and Ooi (1998) to put forward the idea that the formation of the illusory-O is contingent on the inner and outer rectangular segments being amodally integrated, which occurs only when they have the same luminance contrast polarity. This contingency idea is consistent with the notion the main casual factor for illusory surface (modal) completion is the visual system's tendency to amodally complete separated elements (Kanizsa, 1955). Together, our Experiments 1 and 2 provide a more direct support for this notion. First, Experiment 1 shows that amodal surface interpolation, in the presence of a real occluding surface, is subjected to the same contrast polarity constraint. Then Experiment 2 shows that when the visual system is confronted with geometric cues valid for amodal and modal surface completion, there is a tendency to amodally interpolate only when the separated elements have the same luminance contrast polarity.

We need to point out that the same contrast polarity constraint does not affect the formation of an illusory surface that is not driven by amodal surface integration between two elements. For example, it has been shown the Kanizsa illusory square is perceived even when neighboring pac-man elements have opposite contrast polarity (Prazdny, 1983; Shapley & Gordon, 1983, 1985). This is because the formation of the Kanizsa illusory square is not driven by the amodal surface integration between the neighboring pac-men (He & Ooi, 1998). In fact, when one perceives the Kanizsa illusory square, one also has an impression of each pac-man being amodally completed as a disc in back. Related to this, Spehar (2000) and Spehar and Clifford (2003) made an interesting observation where the perception of the illusory square is degraded when each pac-man was made of one-half white and one-half black sector (opposite contrast polarity). An explanation for this, which is similar to ours, is the two parts of the pac-man with opposite contrast polarity cannot initiate amodal completion to become a full disc. However, Albert (2001) pointed out the disruption of the illusory contour could be due to the Y-junction formed between the contour dividing the black and white parts of the pac-man and the two edges of the pac-man.

The observation of the Kanizsa illusory square with opposite contrast polarity elements motivates the proposal the brain has a contour boundary system that is responsible for surface completion (Grossberg & Mingolla, 1985; Kellman & Shipley, 1991; Shapley & Gordon, 1987; Williams & Hanson, 1996). The contour boundary system is insensitive to luminance contrast polarity and codes the contrast edge. To represent a texture-free surface, the contour boundary system first constructs the borders (outlines) of the surface. Then from the borders, a feature contour system, which carries the luminance and color contrast polarities at the border, fills the interior surface with brightness and hue (e.g., Grossberg & Mingolla, 1985). Accordingly, it is the contour boundary system that determines whether two elements can be completed. Since the contour boundary system is insensitive to luminance contrast polarity, it is expected to complete separated elements with opposite contrast polarity such as those displays in Figures 1b, 2b, 5b, and 8b.

However, our current results and those of He and Ooi (1998) demonstrate a strong influence of luminance contrast polarity (a surface feature cue) on surface completion. This suggests computational models of surface representation need to more heavily weight the contributions of surface feature cues in surface completion. There are two possible ways to do so. The first way is to include feedback interactions in the model (e.g., Albert, 2007). For example, the initially integrated boundary contour representation can be inhibited or vetoed by the feature contour system if the latter system detects an opposite contrast polarity between separated elements. The second way is for the feature contour system to detect both the contour and contrast polarity and represent the surface. In this way, the feature contour system can integrate surface segments when their aligned contours have the same contrast polarity. Several neurophysiological studies of early visual cortical neurons have shown that form (e.g., orientation and edge location) and color/luminance contrast polarity information are often coded by the same neurons (e.g., Friedman, Zhou, & von der Heydt, 2003; Gegenfurtner, Kiper, & Fenstemaker, 1996; Leventhal, Thompson, Liu, Zhou, & Ault, 1995; Zhou, Friedman, & von der Heydt, 2000). In particular, Zhou et al. (2000) found that the majority of neurons in V2 and V4 code both the border ownership (BO) and the local luminance contrast polarity (CP) information. These border ownership selective neurons are crucial for representing surface separation (surface limit/extension), which is likely to contribute to surface completion (Baylis & Driver, 1995; Fang, Boyaci, & Kersten, 2009; Koffka, 1935; Nakayama et al., 1995; Nakayama & Shimojo, 1990; Qiu & von der Heydt, 2005; von der Heydt, Peterhans, & Baumgartner, 1984; Zhou et al., 2000).

While it is beyond the scope of this paper, we recognize the future need to investigate whether the same contrast polarity constraint can be generalized to more complex images. Our studies have thus far used relatively simple displays wherein the element's luminance contrast polarity can be easily defined, as all elements are viewed against a background with the same luminance specification. Such simple displays allow us to explain our results based, presumably, on an early and local surface contour process. But how does the visual system represent more complex surface layouts? For instance, when separated gray surface segments are seen against a background surface with locally abrupt changes in luminance levels? In this case, it is not easy to define the overall luminance contrast polarity of the contours. This scenario leads us to speculate that since the goal of amodal surface completion is to specify a large surface entity, a higher level of global surface representation process must be involved in amodal surface integration. The higher level would ensure that for complex surface layouts the similarity of the overall lightness of the surface segments would be the determining factor used for surface integration. To be precise, we speculate the later stage of global surface representation process could override the same contrast polarity constraint of the early and local surface contour process, if the later process identifies two surface segments as having a similar overall lightness. The simple stimuli employed in our experiments are able to show the same luminance contrast polarity constraint because with the same homogeneous background used, the local contrast polarity (negative vs. positive) is consistent with the perceived global lightness of the surface segments (black vs. white).

Acknowledgments

This study was supported by a grant from the National Institutes of Health (EY015804) to TLO and ZJH.

Commercial relationships: none.
Corresponding authors: Teng Leng Ooi and Zijiang J. He.
Emails: tlooi@salus.edu; zjhe@louisville.edu.
Address: Department of Basic Sciences, Pennsylvania College of Optometry at Salus University, 8360 Old York Road, Elkins Park, PA 19027, USA; Department of Psychological and Brain Sciences, University of Louisville, Louisville, KY 40292, USA.

References

Adelson, E. H., & Movshon, J. A. (1984). Binocular disparity and the computation of two-dimensional motion. *Journal of the Optical Society of America, 1,* 1266.

Albert, M. K. (1993). Parallelism and the perception of illusory contours. *Perception, 22,* 589–595. [PubMed]

Albert, M. K. (2001). Cue interactions, border ownership and illusory contours. *Vision Research, 41,* 2827–2834. [PubMed]

Albert, M. K. (2007). Mechanisms of modal and amodal interpolation. *Psychological Review, 114,* 455–469. [PubMed]

Anderson, B. L., & Barth, H. C. (1999). Motion-based mechanisms of illusory contour synthesis. *Neuron, 24,* 433–441. [PubMed]

Anderson, B. L., & Julesz, B. (1995). A theoretical analysis of illusory contour formation in stereopsis. *Psychological Review, 102,* 705–743.

Baylis, G. C., & Driver, J. (1995). Obligatory edge assignment in vision: The role of figure and part segmentation in symmetry detection. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 1323–1342.

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10,* 433–436. [PubMed]

Croner, L. J., & Albright, T. D. (1997). Image segmentation enhances discrimination of motion in visual noise. *Vision Research, 37,* 1415–1427. [PubMed]

Del Viva, M. M., Gori, M., & Burr, D. C. (2006). Powerful motion illusion caused by temporal asymmetries in ON and OFF visual pathways. *Journal of Neurophysiology, 95,* 3928–3932. [PubMed] [Article]

Duncan, R. O., Albright, T. D., & Stoner, G. R. (2000). Occlusion and the interpretation of visual motion: Perceptual and neuronal effects of context. *Journal of Neuroscience, 20,* 5885–5897. [PubMed] [Article]

Fang, F., Boyaci, H., & Kersten, D. (2009). Border ownership selectivity in human early visual cortex and its modulation by attention. *Journal of Neuroscience, 29,* 460–465. [PubMed] [Article]

Fantoni, C., Bertamini, M., & Gerbino, W. (2005). Contour curvature polarity and surface interpolation. *Vision Research, 45,* 1047–1062. [PubMed]

Friedman, H. S., Zhou, H., & von der Heydt, R. (2003). The coding of uniform colour figures in monkey visual cortex. *The Journal of Physiology, 548,* 593–613. [PubMed] [Article]

Gegenfurtner, K. R., Kiper, D. C., & Fenstemaker, S. B. (1996). Processing of color, form, and motion in macaque area V2. *Visual Neuroscience, 13,* 161–172. [PubMed]

Grossberg, S., & Mingolla, E. (1985). Neural dynamics of form perception: Boundary completion, illusory figures, and neon color spreading. *Psychological Review, 92,* 173–211. [PubMed]

Guzman, A. (1969). Decomposition of a visual scene into three-dimensional bodies. In A. Grasselli (Ed.), *Automatic interpretation and classification of images* (pp. 243–276). New York: Academic Press.

He, Z. J., & Nakayama, K. (1994). Apparent motion determined by surface layout not by disparity or three-dimensional distance. *Nature, 367,* 173–175. [PubMed]

He, Z. J., & Ooi, T. L. (1998). Illusory-contour formation affected by luminance contrast polarity. *Perception, 27,* 313–335. [PubMed]

He, Z. J., & Ooi, T. L. (1999). Perceptual organization of apparent motion in the Ternus display. *Perception, 28,* 877–892. [PubMed]

Kanizsa, G. (1955). Margini quasi percettivi in campi con stimolazione omogenea. *Rivista di Psicologia, 49,* 7–30 [Quasiperceptual margins in homogeneously stimulated fields]. In S. Petry & G. E. Meyer (Eds.), *The perception of illusory contours* (pp. 40–49). New York: Springer.

Kanizsa, G. (1979). *Organization in vision: Essays on gestalt perception*. New York: Praeger.

Kellman, P. J., & Cohen, M. H. (1984). Kinetic subjective contours. *Perception & Psychophysics, 35,* 237–244. [PubMed]

Kellman, P. J., Garrigan, P., & Shipley, T. F. (2005). Object interpolation in three dimensions. *Psychological Review, 112,* 586–609. [PubMed]

Kellman, P. J., & Shipley, T. F. (1991). A theory of visual interpolation in object perception. *Cognitive Psychology, 23,* 141–221. [PubMed]

Koffka, K. (1935). *Principles of gestalt psychology*. New York: Harcourt, Brace and Company.

Leventhal, A. G., Thompson, K. G., Liu, D., Zhou, Y., & Ault, S. J. (1995). Concomitant sensitivity to orientation, direction, and color of cells in layers 2, 3, and 4 of monkey striate cortex. *Journal of Neuroscience, 15,* 1808–1818. [PubMed]

Lorenceau, J., & Shiffrar, M. (1992). The influence of terminators on motion integration across space. *Vision Research, 32,* 263–273. [PubMed]

Nakayama, K., He, Z. J., & Shimojo, S. (1995). Visual surface representation: A critical link between lower-level and higher level vision. In S. M. Kosslyn & D. N. Osherson (Eds.), *Vision: An invitation to cognitive science* (p. 1–70). Cambridge, MA: MIT Press.

Nakayama, K., & Shimojo, S. (1990). Toward a neural understanding of visual surface representation. *Cold Spring Harbor Symposia on Quantitative Biology, 55,* 911–924. [PubMed]

Nakayama, K., Shimojo, S., & Silverman, G. H. (1989). Stereoscopic depth: Its relation to image segmentation, grouping, and the recognition of occluded objects. *Perception, 18,* 55–68. [PubMed]

Nakayama, K., & Silverman, G. H. (1985). Detection and discrimination of sinusoidal grating displacements. *Journal of the Optical Society of America A, Optics and Image Science, 2,* 267–274. [PubMed]

Pelli, D. G. (1997). The VideoToolBox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10,* 437–442. [PubMed]

Prazdny, K. (1983). Illusory contours are not caused by simultaneous brightness contrast. *Perception & Psychophysics, 34,* 403–404. [PubMed]

Qiu, F. T., & von der Heydt, R. (2005). Figure and ground in the visual cortex: V2 combines stereoscopic cues with Gestalt rules. *Neuron, 47,* 155–166. [PubMed] [Article]

Rock, I. (1983). *The logic of perception*. Cambridge, MA: MIT Press.

Rubin, N. (2001). The role of junctions in surface completion and contour matching. *Perception, 30,* 339–366. [PubMed]

Sekuler, A. B. (1994). Local and global minima in visual completion: Effects of symmetry and orientation. *Perception, 23,* 529–545. [PubMed]

Shapley, R., & Gordon, J. (1983). A nonlinear mechanism for the perception of form. *Investigative Ophthalmology and Visual Science, 24,* 238.

Shapley, R., & Gordon, J. (1985). Nonlinearity in the perception of form. *Perception & Psychophysics, 37,* 84–88. [PubMed]

Shapley, R., & Gordon, J. (1987). The existence of interpolated illusory contours depends on contrast and spatial separation. In S. Petry & G. E. Meyer (Eds.), *The perception of illusory contours*. New York: Springer-Verlag.

Shimojo, S., Silverman, G. H., & Nakayama, K. (1989). Occlusion and the solution to the aperture problem for motion. *Vision Research, 29,* 619–626. [PubMed]

Spehar, B. (2000). Degraded illusory contour formation with non-uniform inducers in Kanizsa configurations: The role of contrast polarity. *Vision Research, 40,* 2653–2659. [PubMed]

Spehar, B., & Clifford, C. W. G. (2003). When does illusory contour formation depend on contrast polarity? *Vision Research, 43,* 1915–1919. [PubMed]

Stoner, G. R., & Albright, T. D. (1996). The interpretation of visual motion: Evidence for surface segmentation mechanisms. *Vision Research, 36,* 1291–1310.

Su, Y., Ooi, T. L., & He, Z. J. (2004). Surface and motion integration determined by luminance contrast polarity [Abstract]. *Journal of Vision, 4*(8):888, 888a, http://journalofvision.org/4/8/888/, doi:10.1167/4.8.888.

Tse, P. U. (1999). Volume completion. *Cognitive Psychology, 39,* 37–68. [PubMed]

van der Smagt, M. J., Breij, E. C. W., & van de Grind, W. A. (2000). Spatial structure, contrast polarity and motion integration. *Vision Research, 40,* 2037–2045. [PubMed]

van der Smagt, M. J., & van de Grind, W. A. (1999). Integration and segregation of local motion signals: The role of contrast polarity. *Vision Research, 39,* 811–822. [PubMed]

von der Heydt, R., Peterhans, E., & Baumgartner, G. (1984). Illusory contours and cortical neuron responses. *Science, 224,* 1260–1262. [PubMed]

Watanabe, T. (1997). Velocity decomposition and surface decomposition-reciprocal interactions between motion and form processing. *Vision Research, 37,* 2879–2889. [PubMed]

Watamaniuk, S. N. J., & McKee, S. P. (1995). Seeing motion behind occluders. *Nature, 377,* 720–730. [PubMed]

Wehrhahn, C., & Rapf, D. (1992). ON- and OFF-pathways form separate neural substrates for motion perception: Psychophysical evidence. *Journal of Neuroscience, 12,* 2247–2250. [PubMed] [Article]

Williams, L. R., & Hanson, A. R. (1996). Perceptual completion of occluded surfaces. *Computer Vision and Image Understanding, 64,* 1–20.

Yin, C., Kellman, P. J., & Shipley, T. F. (1997). Surface completion complements boundary interpolation in the visual integration of partly occluded objects. *Perception, 26,* 1459–1479. [PubMed]

Yin, C., Kellman, P. J., & Shipley, T. F. (2000). Surface integration influences depth discrimination. *Vision Research, 40,* 1969–1978. [PubMed]

Yonas, A., Craton, L. G., & Thompson, W. B. (1987). Relative motion: Kinetic information for the order of depth at an edge. *Perception & Psychophysics, 41,* 53–59. [PubMed]

Zhou, H., Friedman, H. S., & von der Heydt, R. (2000). Coding of border ownership in monkey visual cortex. *Journal of Neuroscience, 20,* 6594–6611. [PubMed] [Article]