*Research Article*

# Modal and Amodal Completion Generate Different Shapes

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ABSTRACT—*Mechanisms of contour completion are critical for computing visual surface structure in the face of occlusion. Theories of visual completion posit that mechanisms of contour interpolation operate independently of whether the completion is modal or amodal—thereby generating identical shapes in the two cases. This identity hypothesis was tested in two experiments using a configuration of two overlapping objects and a modified Kanizsa configuration. Participants adjusted the shape of a comparison display in order to match the shape of perceived interpolated contours in a standard completion display. Results revealed large and systematic shape differences between modal and amodal contours in both configurations. Participants perceived amodal (i.e., partly occluded) contours to be systematically more angular—that is, closer to a corner—than corresponding modal (i.e., illusory) contours. The results falsify the identity hypothesis in its current form: Corresponding modal and amodal contours can have different shapes, and, therefore, mechanisms of contour interpolation cannot be independent of completion type.*

The multiplicity of objects in the natural environment and the loss of one spatial dimension during image projection ensure that occlusion is a ubiquitous problem that all visual organisms must face. Occlusion poses a difficult challenge to the computation of visual surface structure because it leads many surface regions in a scene to have no counterparts in the retinal images. As a result, many physically continuous objects appear on the retinas only as disparate fragments. Their continuity, therefore, must be derived by visual mechanisms of contour completion.

The most common form of visual completion occurs when portions of an object are hidden behind another object—but the former object is nevertheless perceived to be a single continuous entity (see Fig. 1a). This is known as amodal completion because, despite the vivid percept of object unity, observers do not actually see a contour (i.e., a contrast border) in image regions where the completion occurs (Michotte, Thines, & Crabbe, 1964/1991). A second form of completion occurs when portions of an object are camouflaged by an underlying surface—because this underlying surface happens to project the same luminance and color as the nearer object (see Fig. 1c). This form of completion is known as modal completion because observers perceive a contrast border—an *illusory contour*—in image regions that contain no contrast (thus, an observer's percept has the same "mode" as if a contour were actually present).

Researchers have maintained that, these phenomenological differences notwithstanding, modal and amodal interpolation result from a common mechanism (or a common set of mechanisms) that operates independently of completion type (see Kellman & Shipley, 1991; Kellman, Yin, & Shipley, 1998; Shipley & Kellman, 1992). In particular, contour interpolation is postulated to occur independently of any depth information that specifies whether the interpolating contour is farther and occluded or nearer and camouflaged. Once interpolation has occurred, the same interpolated contour may become either modal or amodal, depending on available depth information.

An important prediction of this *identity hypothesis* is that identical contour shapes are interpolated in modal and amodal completion. Indeed, this *identical-shapes* claim has historically played an important role in the development of the identity hypothesis—as informal observations concerning the corresponding shapes of modal and amodal contours initially provided the primary motivation for the hypothesis. In particular, researchers noted that when the two perceived objects in a *self-splitting figure* (Petter, 1956; see Fig. 1b) undergo a depth reversal, they tend to maintain their perceived shapes (Kellman & Shipley, 1991; Shipley & Kellman, 1992). Thus, whether one perceives the vertically oriented oval in Figure 1b as being in front (hence modally completed) or behind (hence amodally completed), its interpolated shape appears the same. Similarly, in Kanizsa-triangle displays, the interpolated triangular surface appears identically shaped whether it is completed modally (in front of three black disks; see Fig. 1c) or amodally (seen through three portholes; see Fig. 1d). These observations led Kellman and Shipley to postulate that mechanisms of visual completion must operate independently of completion type.

The identity hypothesis has the benefit of parsimony. There would be little reason to posit two distinct mechanisms of contour interpolation if modal and amodal completion always generated the same contour shapes (and displayed identical dependencies on image properties). Contrapositively, however, it follows that if systematic differences between the shapes of corresponding modal and amodal contours are revealed, these would constitute evidence against the identity hypothesis—at least in its current form, which postulates an independence

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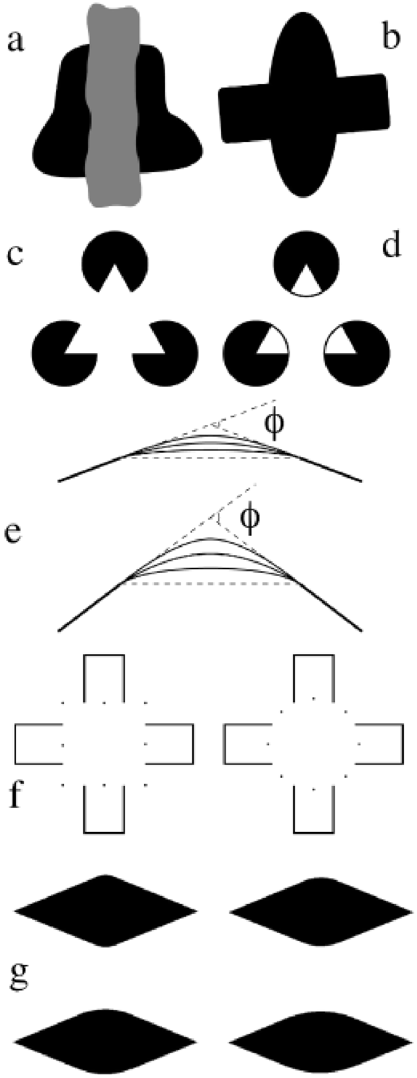


**Fig. 1.** Illustrations of visual completion. In the example of amodal completion (a), the two black regions are disparate fragments in the image, but are perceived to belong to a single amodally completed surface extending behind the gray occluder. The self-splitting figure (b) is perceived to contain two overlapping objects that undergo spontaneous depth reversals—thereby switching which object is modally completed (in front) and which one is amodally completed (in the back). In the modal version of the Kanizsa triangle (c), a unitary white surface is seen to partly occlude three black disks. In the amodal version of the Kanizsa triangle (d), a unitary white surface is seen to extend behind a surface containing three portholes. The identity hypothesis was motivated by the observation that the modal and amodal variants of both the self-splitting figure and the Kanizsa displays generate identical completed shapes. The illustration in (e) shows that inducer pairs with smaller turning angles (top) allow less room for the shape of the interpolating contour to vary than do those with larger turning angles (bottom). Small turning angles thus make any shape differences between modal and amodal completion less likely to be detected. The *Koffka crosses* in (f) demonstrate that the placement of a small number of dots can alter the perceived shapes of illusory contours. The illustration in (g) shows four levels of smoothing applied to a diamond shape with a turning angle of 45°. This configuration served as the comparison display in the experiments. Participants adjusted the degree of smoothing applied to its top and bottom vertices, in order to match the shape of the perceived interpolated contour in a standard completion display. The four levels depicted have normalized smoothing measures of .2, .4 (top row), .6, and .8 (bottom row), respectively.

between mechanisms of contour interpolation and processes that determine completion type. Therefore, a direct comparison of the shapes of corresponding modal and amodal contours assumes great importance in testing the identity hypothesis. Although previous work has suggested some differences between modal and amodal completion—for example, that modal completion requires more "energy" (Tommasi, Bressan, & Vallortigara, 1995), that amodal completion can tolerate inflections whereas modal completion cannot (Takeichi, Nakazawa, Murakami, & Shimojo, 1995), that visual attention spreads differently to modally and amodally completed surfaces (Davis & Driver, 1997), and, more recently, that modal and amodal completion are subject to different photometric constraints (Anderson, Singh, & Fleming, 2002)—a direct comparison of the shapes of corresponding modal and amodal contours (i.e., contours interpolated across the same pairs of inducing edges) has not been carried out.[1] Part of the reason, no doubt, lies in the dearth of good experimental methods for measuring the shapes of interpolated contours and, especially, of methods that work symmetrically for illusory contours and partly occluded contours (i.e., that do not themselves introduce asymmetries between the two cases; see the next section). The experiments reported in this article employed an adjustment method in which observers adjust the shape of a comparison display in order to match the perceived shape of an interpolated contour.

The experiments were guided by the realization that the displays that have traditionally motivated the identity hypothesis (e.g., the self-splitting figure and the Kanizsa displays in Figs. 1b–1d) share a property that greatly restricts their generality. In particular, the angle through which the interpolating contour must turn in proceeding from one inducing edge to the other—its *turning angle*—either is zero (in the case of the linear interpolation required in the Kanizsa triangle; Figs. 1c and 1d) or else has a small magnitude (in the case of the curved interpolation required for the oval in the self-splitting figure; Fig. 1b). As Figure 1e makes clear, given a pair of relatable edges, smaller turning angles (top of Fig. 1e) simply allow less room for the shape of the interpolating contour to vary than larger turning angles do (bottom of Fig. 1e). Indeed, in the limiting case in which the turning angle becomes zero, the set of possible shapes simply collapses onto one—that is, the straight-line interpolation.[2] This suggests that if there are in fact systematic differences between the shapes of corresponding modal and amodal contours (i.e., contours interpolated across the same pairs of inducing edges), they are more likely to be revealed in cases in which the interpolating contour must turn through a large turning angle (e.g., in the bottom, rather than the top, display of Fig. 1e). Therefore, the current experiments used completion displays that required the interpolating contour to turn through relatively large angles.[3]

[1]Perhaps the most relevant study in this regard is that of Anderson et al. (2002). In their "serrated-edge illusion" (Fig. 19, p. 184), reversing the sign of binocular disparity led to differently interpolated surfaces, because the inducing edges were paired differently in the two cases. By contrast, the current study compared the perceived shapes of corresponding modal and amodal contours—interpolated across the same pairs of inducing edges.

[2]This follows under any reasonable model of contour interpolation. Indeed, all that is required is that no unnecessary loops or inflections be introduced—a property that all existing models share (see, e.g., Fantoni & Gerbino, 2003; Kellman & Shipley, 1991; Kubovy & Gepshtein, 2000; Liu, Jacobs, & Basri, 1999; Singh & Hoffman, 1999; Takeichi et al., 1995; Ullman, 1976).

[3]Although the turning angles used in the experiments were relatively large, they were still well within the 90° range permitted by the criterion of edge relatability (Kellman & Shipley, 1991).

## EXPERIMENTS

The experiments used an adjustment method to investigate whether systematic shape differences exist between modally and amodally completed contours. Participants adjusted the shape of a comparison display in order to match the perceived shape in a standard completion display. The comparison display was separated spatially from the standard completion display. This separation served two purposes. First, it ensured that the measurement technique itself had minimal influence on the perceived shapes of the interpolated contours. It is known that the placement of a few dots in an illusory-contour display can alter its perceived shape (e.g., the Koffka crosses; see Fig. 1f). For this reason, measurement techniques that use the positional adjustment of superimposed dot probes typically flash these probes very briefly. For current purposes, however, there was a second concern with the method of dot positional adjustment—namely, it does not generalize symmetrically to the occluded-contour case. In the occluded-contour case, the interpolated contour lies, by definition, behind the occluder, whereas the dot probe must lie—in order to be visible—in front. This introduces an asymmetry relative to the illusory-contour case, in which both the interpolated contour and the probe are located nearer to the observer than the second—in this case, occluded—surface. As a result, the measurement technique itself may introduce differences between the modal and amodal cases. Spatially separating the comparison display from the standard completion display eliminates such asymmetries because the relative depth of the interpolated contour (i.e., occluded or occluding) no longer constrains the depth placement of the contour to be adjusted by the participant.

The comparison display in the current experiments consisted of a diamond-shaped figure (see Fig. 1g) whose left and right ends matched the inducing contours of a standard completion display (e.g., Fig. 2a). Participants adjusted the degree of smoothing of the top and bottom vertices of the comparison display (see the parametric variation displayed schematically in Fig. 1g) in order to match the perceived shape of the interpolated contour in the standard display. In the extreme case, the interpolation consisted simply of the linear extensions of the two edges meeting in a corner. Incrementally smoothed versions were then obtained by convolving this corner interpolant with one-dimensional masks (or kernels) of increasing sizes; the larger the mask, the greater the degree of smoothing. The mask size set by the participant was then normalized by the length of the diamond's side, in order to obtain a scale-invariant measure of smoothing. Because mask size was constrained to not exceed the length of the diamond's side, this measure yielded values between 0 and 1. (Fig. 1g shows four different levels of smoothing applied to a comparison display. These have normalized measures of .2, .4, .6, and .8, respectively.)[4]

[4]One-dimensional convolutions, applied along contours, are commonly used in computer vision to smooth out contour perturbations of different sizes (see, e.g., Asada & Brady, 1986; Mokhtarian & Mackworth, 1992). The degree of variation depicted schematically in Figure 1e can also, of course, be parametrized in other ways. An alternative possibility is one based on a recent model of contour interpolation by Fantoni and Gerbino (2003). In their model, interpolated contour shape results from the combination of two vector fields: a *GC field* (capturing the tendency toward the good continuation of each separate inducer) and an *MP field* (capturing the minimal-path tendency, i.e., the tendency to minimize total curve length). The relative strengths of these two components are captured by the *GC-MP contrast*, which is calculated as $[GC - MP]/[GC + MP]$. Different values of this measure yield different levels of smoothing of the interpolated contour.

An important characteristic of the stimulus displays was that binocular disparity was used to define the depth ordering of surfaces (and this, in turn, determined whether the interpolated contours were modal or amodal; see, e.g., Fig. 2). Although monocular manipulations are often used to effect a switch between modal and amodal variants of a completion display, these manipulations, unfortunately, generate significant changes in an image's junction structure. For example, the amodal version of the Kanizsa display (Fig. 1d) contains multiple T-junctions that are absent in the modal version (Fig. 1c). As a result, any differences obtained across the two versions of the display cannot easily be attributed to the manipulation of modal versus amodal, because it is also possible that these differences arise simply from this low-level junction structure (cf. Ringach & Shapley, 1996). Manipulating completion type using binocular disparity has the advantage that the modal and amodal variants contain the same junctions and other low-level features. Indeed, the very same pair of images is presented to the observer in the two cases—only the eye to which each image is presented is switched. (Note that this also means that the modal and amodal versions of the displays are also balanced with respect to global factors, such as symmetry, which have been shown to influence completion; e.g., Sekuler, Palmer, & Flynn, 1994.)

Experiment 1 compared the perceived shapes of corresponding modal and amodal contours using a configuration of two overlapping objects, whereas Experiment 2 performed the analogous comparison using a two-inducer version of the Kanizsa display. Both displays were designed to generate relatively large turning angles across inducers.

### Experiment 1

#### *Method*

*Participants.* Fourteen undergraduate students from Rutgers University participated in the experiment. All were naive to the purpose of the experiment and had normal or corrected-to-normal visual acuity.

*Stimuli and Apparatus.* The stimuli consisted of a standard completion display and a comparison display. The standard display was presented on the left half of the screen and consisted of two black overlapping shapes (screen luminance = 0.02 cd/m$^2$), presented against a dark-gray background (screen luminance = 3 cd/m$^2$): a vertically oriented ellipse and a horizontally oriented diamond (see Fig. 2a). The diamond was given either a near disparity or a far disparity of 10 min of arc relative to the ellipse, depending on completion type (see Figs. 2b and 2c for schematic depictions of the corresponding percepts). The height of the ellipse was 10°. Its width could take one of four values—1.4°, 2.5°, 3.6°, or 4.7°—thus generating four possible levels of separation between the inducers. The width of the diamond was set to be 4.2° longer than the width of the ellipse; the diamond's width was thus 5.6°, 6.7°, 7.8°, or 8.9°. The height of the diamond was determined on the basis of the required value of the turning angle between the inducers, which was either 45° or 75°.

The comparison display was presented on the right half of the screen and consisted of a single diamond shape whose width and lateral angles were identical to those of the diamond in the standard display. The degree of smoothing applied to its top and bottom corners was under the control of the participants. Smoothing was achieved by convolving the contour in the neighborhood of a corner with a one-dimensional uniform mask of a certain size. (This effectively replaces each point on the contour segment with the mean of the coordinate values of all contour points that lie within $N/2$ units of arc-length distance, where $N$ = mask size. Larger mask sizes thus generate systematically greater levels of smoothing.) Participants adjusted the degree of smoothing using a

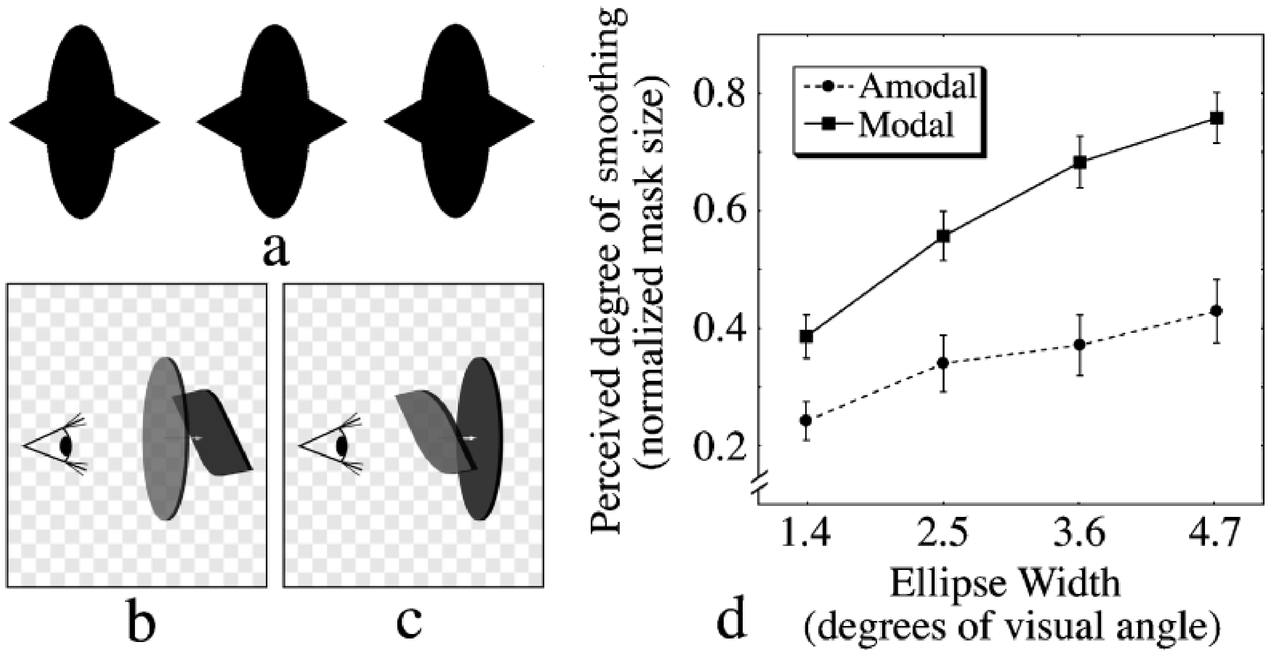


**Fig. 2.** Stimuli and results from Experiment 1. An example of the stereoscopic stimuli used is shown in (a). Depending on which pair of images was fused, the stereogram generated the percept of a diamond-shaped surface floating either (b) behind or (c) in front of the vertical ellipse. In (d), the perceived degree of smoothing is graphed as a function of the width of the ellipse, separately for amodally and modally completed contours. The error bars correspond to standard errors of the means.

computer mouse (see Fig. 1g for a sequence of such smoothings applied to the diamond with a turning angle of 45°).

The stimuli were presented on a high-resolution 22-in. monitor. Participants viewed the stimuli from a distance of 61 cm, under conditions of low ambient illumination. They viewed the stimuli through LCD shutter goggles that alternated between the two eyes at a rate of 150 Hz—resulting in a refresh rate of 75 Hz for each eye.

*Procedure.* On each trial, the standard completion display was first presented by itself for 5 s. A low-pitched beep then signaled the appearance of the comparison display on the right half of the screen. Participants adjusted the degree of smoothing in the top and bottom corners of the diamond in the comparison display (the two varied symmetrically), in order to match the perceived shape of the interpolated contours in the completion display.

Each participant performed 80 experimental adjustments: 2 (modal vs. amodal) × 4 (ellipse widths) × 2 (turning angles) × 5 (repetitions). These were preceded by 16 practice adjustments.

### Results

Figure 2d shows the results for Experiment 1. The results reveal a large difference between the perceived shapes of corresponding modal and amodal contours ($\eta = .81$): Amodally completed contours were perceived to be systematically less smoothed (i.e., closer to being a corner) than corresponding modal contours. This effect of completion type was highly significant, $F(1, 13) = 24.15$, $p < .001$.[5] Moreover, separate analyses of the two levels of turning angle revealed that the effect of completion type was significant in each case: $F(1, 13) = 15.34$, $p < .01$, $\eta = .74$ (turning angle of 45°), and $F(1, 13) = 28.93$, $p < .001$, $\eta = .83$ (turning angle of 75°).[6]

The main effects of oval width and turning angle were also significant: Overall, inducers with greater (i.e., sharper) turning angles generated interpolated contours that were more angular than the interpolated contours generated by inducers with smaller turning angles, $F(1, 13) = 12.09$, $p < .01$, $\eta = .69$, and increasing the oval width (and hence the separation between the inducers) generated interpolated contour shapes that were more smoothed, $F(3, 39) = 37.48$, $p < .001$, $\eta = .86$. The latter effect is consistent with Fantoni and Gerbino's (2003) finding that decreasing the support ratio of amodal contours leads to more rounded interpolated shapes.[7] In addition, however, the current results revealed an interaction between support ratio and completion type: Increasing the separation between inducers (and hence decreasing support ratio) had a greater influence on the shapes of modal contours than on those of amodal contours, $F(3, 39) = 11.76$, $p < .001$, $\eta = .70$.

[5]The reported statistics are based throughout on the *angular transformation*, $g(y) = 2\arcsin(\sqrt{y}) - \pi/2$, applied to the normalized smoothing measure (which ranges from 0 to 1) in order to improve the normality of its distribution (Hoaglin, Mosteller, & Tukey, 1991). All reported significant effects (in both experiments) were in fact highly robust to this transformation; that is, they were obtained both with and without it.

[6]These effects were also highly significant when the raw smoothing measure (i.e., convolution mask size) was used rather than the normalized measure. This was to be expected because the normalized measure is in fact more conservative: It explicitly takes into account the fact that some of the increase in the adjusted mask size is simply due to an increase in the overall size of the diamond shape (e.g., as inducer separation increases), and it factors out this contribution.

[7]Support ratio is defined as the ratio of interpolated contour length to total contour length (interpolated plus physically specified; see Shipley & Kellman, 1992). Because the current experiments did not vary the lengths of the physically specified contours, increasing the separation between inducers led to systematically lower support ratios.

### Experiment 2

The generality of the results obtained with the overlapping-objects configuration was tested in Experiment 2 by performing the same comparison using a Kanizsa-type configuration. The standard Kanizsa display (Figs. 1c and 1d) was modified to have two inducers rather than three. This manipulation forced the interpolating contours to turn through larger turning angles.

*Method*

*Participants.* A new group of 14 naive participants took part in the experiment.

*Stimuli and Apparatus.* As in Experiment 1, the stimuli consisted of a standard completion display and a comparison display. The standard display consisted of a black horizontally oriented diamond (screen luminance = 0.02 cd/m$^2$) and two medium-gray vertically oriented ellipses (screen luminance = 27 cd/m$^2$; see Fig. 3a). The middle portion of the diamond was camouflaged by a background of identical luminance. The diamond was given either a near disparity or a far disparity of 10 min of arc relative to the ellipses, depending on completion type (see Figs. 3b and 3c for schematic depictions of the corresponding percepts). The two ellipses were 8.3° long and 2.8° wide. The horizontal separation between them could take one of four values: 1.4°, 2.5°, 3.6°, or 4.7°. As in Experiment 1, the height of the diamond was determined on the basis of the required value of the turning angle between the inducers, which was 45° or 75°.

The comparison display, the apparatus, and the viewing conditions were identical to those in Experiment 1.

*Procedure.* The experimental procedure was identical to that of Experiment 1. Each participant performed 80 experimental adjustments: 2 (modal vs. amodal) × 4 (inducer separations) × 2 (turning angles) × 5 (repetitions). These were preceded by 16 practice adjustments.

*Results*

Figure 3d shows the results for Experiment 2. As in Experiment 1, amodal contours were perceived to be systematically less smoothed (i.e., closer to being a corner) than corresponding modal contours, $F(1, 13) = 7.25$, $p = .0185$, $\eta = .60$. Moreover, separate analyses of the two levels of turning angle revealed that the effect of completion type was statistically significant in each case, $F(1, 13) = 7.31$, $p = .018$, $\eta = .60$ (turning angle of 45°), and $F(1, 13) = 6.2$, $p = .027$, $\eta = .57$ (turning angle of 75°).

The main effects of inducer separation and turning angle were also significant: $F(3, 39) = 37.08$, $p < .001$, $\eta = .86$ (ellipse separation), and $F(1, 13) = 120.33$, $p < .001$, $\eta = .95$ (turning angle). As in Experiment 1, increasing the separation between the inducing edges—in this case, by increasing the separation between the ellipses—generated interpolated contour shapes that were more smoothed. However, the interaction between inducer separation and completion type was not statistically reliable, $F(3, 39) = 2.42$, $p = .08$, $\eta = .25$.

## DISCUSSION

In the context of both the two-overlapping-objects configuration (Experiment 1) and the two-inducer Kanizsa configuration (Experiment 2), the experiments revealed systematic differences between the shapes of corresponding modal and amodal contours. In particular, observers consistently perceived amodally interpolated contours to be more angular—that is, more like a corner—than their modal counterparts. These differences stand in sharp contrast to prevalent claims that modal and amodal completion generate identical shapes.

There appear to be two main reasons why differences between the shapes of corresponding modal and amodal contours have not previously been reported (but recall footnote 1). First, although the primary motivation for the identity hypothesis initially arose from the informally observed identity of the shapes of modal and amodal contours, experimental tests of the identity hypothesis have focused largely on comparing the strengths of modal and amodal completion, rather than their interpolated shapes. Second, and perhaps more important, the displays that have been used to argue for the identical-shapes claim have typically shared the restrictive property that each interpolated contour needs to turn through only a relatively small angle. As noted earlier, small turning angles simply allow less room for the shape of the interpolated contour to vary (Fig. 1e)—thereby making any shape differences less likely to be detected. Using displays with larger turning angles, the current experiments revealed substantial differences between the shapes of corresponding modal and amodal contours.

The presence of systematic shape differences between modal and amodal completion contradicts the currently held version of the identity hypothesis—namely, that mechanisms of contour interpolation operate independently of completion type. It does not logically follow, however, that modal and amodal completion cannot share a common mechanism. Indeed, a natural hypothesis suggested by the current results is that the two forms of completion share a common interpolation mechanism, but this mechanism involves a free parameter (responsible for generating the parametric variation in the smoothing level) that can take on different values for modal and amodal completion. In other words, the shape-generation mechanism takes into account whether the completion is modal or amodal; however, this is done simply by resetting a parameter value within the same mechanism, rather than using an altogether different mechanism.[8] Thus, unlike the currently held version, this *weak identity hypothesis* allows the shapes of corresponding modal and amodal contours to differ along certain dimensions—while nevertheless preserving the common-mechanism component of the original hypothesis. An important implication of this hypothesis is that interpolated contour shape is determined not only—as is commonly assumed—by geometric factors, such as the relative positions, orientations, and lengths of the inducing edges, but also by the type of completion. Future work will be needed to test the proposed weak identity hypothesis—ideally, by using multiple techniques for measuring interpolated-contour shapes (see, e.g., Gold, Murray, Bennett, & Sekuler, 2000)—and to fully characterize the parametric variation of smoothing level in terms of visual mechanisms.

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[8]In terms of Fantoni and Gerbino's (2003) recent model of contour interpolation, this parameter would be the GC-MP contrast (see footnote 4). Alternatively, it may simply be that amodal completion has greater extrapolation strength than modal completion—a hypothesis that is also consistent with Petter's rule (Kellman & Shipley, 1991; Petter, 1956; Singh, Hoffman, & Albert, 1999).

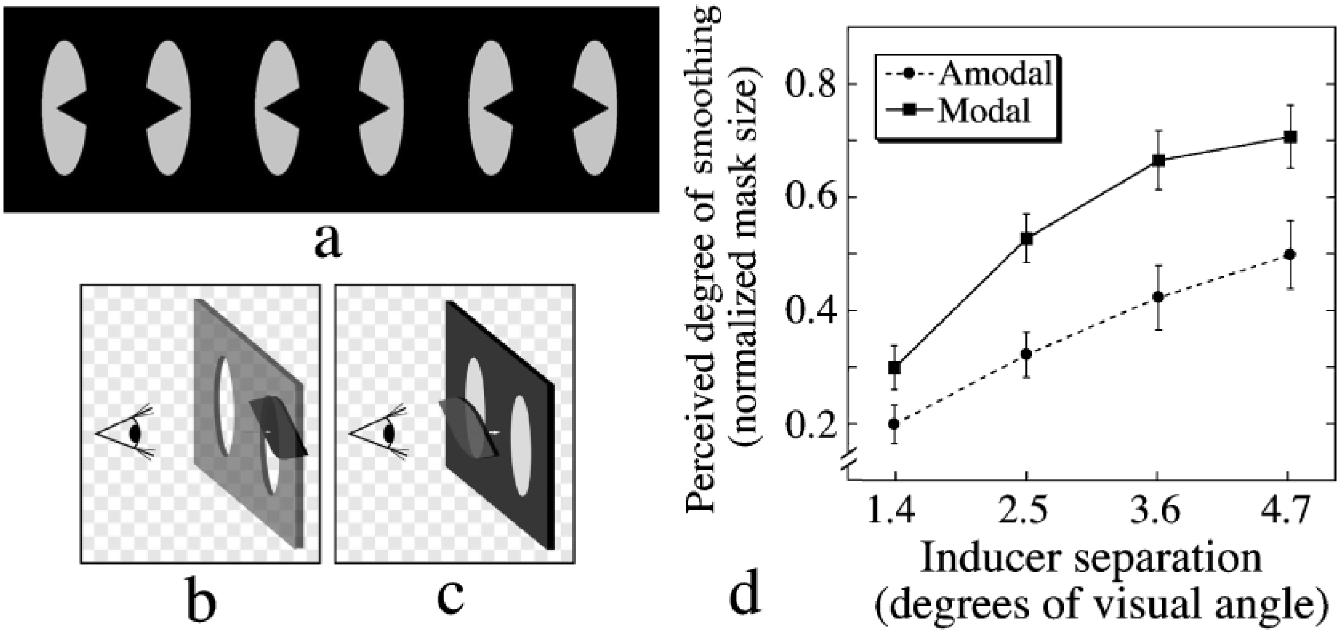


**Fig. 3.** Stimuli and results from Experiment 2. The stereoscopic configuration used for the standard completion display is shown in (a). The schematic in (b) portrays the depth layering of surfaces perceived when the inducing contours were given far disparity relative to the vertical ellipses. (Note that the colors have been modified for illustrative purposes.) The schematic in (c) shows the depth layering of surfaces perceived when the inducing contours were given near disparity relative to the ellipses. In (d), the perceived degree of smoothing is graphed as a function of the separation of the inducers, separately for amodally and modally completed contours. The error bars correspond to standard errors of the means.

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