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Surface completion complements boundary interpolation in the visual integration of partly occluded objects

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Abstract. Previous research on perceptual completion has emphasized how the spatial relationships of edges influence the visual integration of the image fragments that result from partial occlusion. We report studies testing the hypothesis that the similarity of surface features also influences visual integration, complementing edge interpolation processes. Using displays that separated edge interpolation processes from surface-feature interpolation processes, we tested the hypotheses that a surface completion process integrates image fragments with similar surface features, and that surface completion is constrained by amodally interpolated and amodally extended boundaries. Both edge relatability and surface-feature similarity were manipulated in a series of paired-comparison and classification tasks. The results of these studies supported the hypotheses and were extended to surface features of colors, textures, and color gradients. Results also suggest that, under certain conditions, surface completion may interact with and influence edge interpolation.

1 Introduction

Many objects in our three-dimensional environment are partially occluded, yet we do not perceive them as being fragmented or incomplete. To understand how we are able to derive integrated representations of objects despite occlusion, we must investigate how the visual system surmounts gaps in the optical input from these objects. Such processes are generally referred to as *visual completion* processes.

Previous theories of visual completion have proposed two different but complementary processes: an edge completion process that interpolates the boundaries between the image fragments, and a surface completion process that 'spreads' surface features such as texture and color (both chromatic and achromatic) within bounded regions (Grossberg and Mingolla 1985; Kellman and Shipley 1991). These stimulus-driven complementary processes produce a representation of the bounded surfaces in the environment. Despite this complementarity, the contribution of the surface-feature-based process has received little attention in previous research. In the studies reported here we attempt to isolate the surface completion process from the edge process in order to assess the contribution of surface features to visual completion.

Visual completion may not only involve separable processes, but contributes to more than one perceptual outcome. A number of studies have dealt with *unit formation*, the integration of noncontiguous image regions projected to the eyes (Kellman and Shipley 1991; Leeuwenberg and van der Helm 1991), whereas other studies have been concerned with recovery of the shape of an object's occluded contour (Gerbino and Salmaso 1985; Sekuler and Palmer 1992; van Lier et al 1994, 1995; Takeichi et al 1995; Takeichi 1995).

The distinction between unification and shape (Koffka 1935; Boselie and Wouterlood 1992; Trick and Enns 1997) may be important for understanding the contributions of edge and surface-feature completion processes. Edge completion processes can provide the solution to both problems: by nature, edge interpolation not only unifies but

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defines shape. Surface features, apart from edges, may contribute primarily to perceptual unit formation by unifying image fragments on the basis of surface-feature similarity. Each of these two processes will be addressed in turn.

1.1 *Characteristics of edge interpolation and edge extension processes*

Several aspects of edge interpolation processes are especially relevant to the current studies. First, edge interpolation is initiated by particular features in the image known as *tangent discontinuities*, that is, sharp corners in edges of projected regions (Guzman 1968; Shipley and Kellman 1990; Wouterlood and Boselie 1992; Sajda and Finkel 1995). Second, the edge *interpolation* mechanism exhibits a general lack of sensitivity to neutral and chromatic color relationships (Shipley and Kellman 1992a). This is consistent with the idea that there are two complementary processes, one for edge perception and the other for surface-feature perception. Third, a set of highly constrained spatial relationships governs whether or not two edges appear to join behind an occluder. The spatial relationships supporting edge interpolation are formally described by the *relatability criterion* (Kellman and Shipley 1991). Intuitively, relatability requires that the interpolated path be a curve that is both smooth (ie differentiable at least once) and monotonic (ie interpolated edges do not bend through more than 90°). Formally, two edges are relatable if

$$0 \leqslant R\cos\theta \leqslant r,$$

where R and r are the perpendiculars of the two edges, and θ is the angle formed by R and r (see figure 1). Formalized as such, relatability is an all or none property of two edges. However, Kellman and Shipley (1991) reported that the interpolated edge is strongest when two edges are collinear, and interpolation strength decreases as the angular disparity of the two edges approaches 90°. The exact relationship between the degree of curvilinearity and the strength of the interpolation remains to be quantified (cf Field et al 1993).

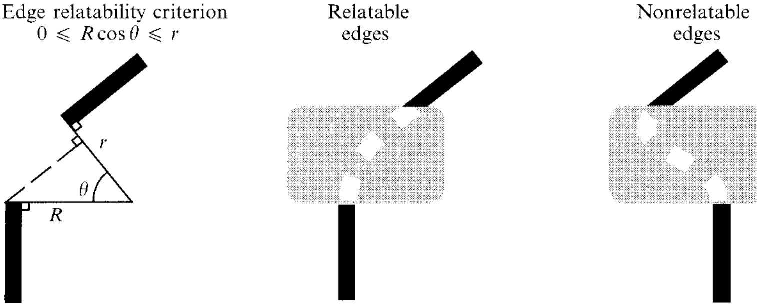

Figure 1. The spatial relationships defining edge relatability (see text).

1.1.1 *Tangent extensions of edges.* It is important to distinguish between phenomena of edge *interpolation* and edge *extension*. Interpolation refers to cases in which an edge bridges a gap between two physically specified edges. There are also cases, however, where an edge perceptually continues behind an occluder but does not meet up with any other edge (Kanizsa 1979). For example, Shimojo and Nakayama (1990) show that in the presence of tangent discontinuities, specifically T-junctions, edges are treated as extending amodally(1) behind the occluder. In the absence of another relatable edge, edges continue behind occluders along *linear* extensions to some extent (Kanizsa 1979; Shimojo and Nakayama 1990; Kellman and Shipley 1991; Wouterlood and Boselie 1992).

(1) Following Michotte et al (1964), visual completion of partly occluded objects has been called 'amodal' completion, while visual completion for color-spreading and illusory figures has been referred to as 'modal'. These terms were intended to describe the phenomenological properties of the completed area.

We will use the term 'tangent extensions' to refer to the straight, amodal edge extensions that are tangent to the partly occluded edge at the point of occlusion.

1.2 *Surface completion*

A surface completion process is hypothesized to complement the edge interpolation process by providing non-edge information to visual integration. Unlike the 'color-blind' edge process (Shipley and Kellman 1992a), a surface completion mechanism would operate upon surface features such as color and texture, integrating similarly featured image fragments together. The phenomenology of surface completion processes has been described by Koffka (1935, page 182), who pointed out that figure–ground segregation for a figure containing a diamond inset in a rectangle (and touching the top and bottom of the rectangle) is aided by the fact that the background rectangle is "uniform in color, so that the factor of equality also contributes to its unity. If this equality is destroyed by coloring the right and the left part of the large oblong differently ... its unity is destroyed. The main feature of the new pattern is the central shape, while the rest is much more difficult to describe."

Kellman and Shipley (1991) have proposed that a surface spreading process may interact with a partly occluded object's tangent extensions to amodally extend that object's boundaries. Figure 2 shows a region that appears to extend amodally behind the rectangle, owing to the T-junctions at the points of boundary intersection. If this region matches the circle in surface texture and color, then the circle may take on the appearance of a hole in the rectangular surface, through which part of the occluded object is seen (see also Metelli et al 1978; Cavedon 1980). The percept of a hole should be strongest when the circular image fragment has been integrated with the surface of the partly occluded object. Since there are no tangent discontinuities in the border of the circle, the process by which the circle and the occluded object are unified is not edge-based. This phenomenon appears to depend on the surface-feature similarity of the circle and the partly occluded region, and also on spatial positioning. Specifically, if the spot falls within the tangent extensions of the visible contours of the partly occluded object, then the circle seems to appear as a hole. If the circle appears outside of the tangent extensions, it appears to be a disk on top of the rectangle.

Surface completion processes would play a critical role when an occluder fragments a surface into many pieces. For example, when we look up at the sky through the leaves of a tree, we have no trouble determining which surface fragments belong to the sky and which belong to the tree. In these cases, surface completion processes integrate all the sky-colored fragments to the unified representation of a background sky. As figure 2 shows, surface completion may have a configural requirement such that surface completion for *figural* objects is constrained within relatable boundaries or tangent extensions.

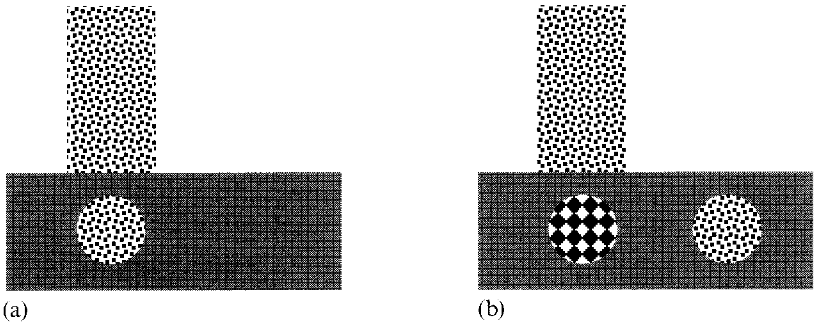
(a) (b)

Figure 2. Because of the configural and surface similarity requirements of surface completion, the circle in (a), being of the same texture as the occluded rectangle and located within the tangent extensions of the rectangle, is more likely to appear as a hole than either circle in (b).

In contrast, the visual integration of *background* fragments seems to be different: in the example of the sky, surface completion proceeds despite the lack of explicit boundaries. Surface completion seems to have some fluid properties, 'spreading' features in all directions until an object boundary is encountered. It may be that surface spreading can be constrained by object boundaries, but does not require the presence of boundaries to operate, as was hypothesized in earlier descriptions of surface spreading (Grossberg and Mingolla 1985; Kellman and Shipley 1991).

Although surface-feature processes cannot directly provide shape information, surface interpolation may complement the edge interpolation processes by providing a different type of information: edge mechanisms play a powerful role in revealing a unit's shape, even in the cases where surface features differ (see figure 3). Surface completion most likely would not give clear shape information, but may give some information about the size and spatial location of the occluded area if the occluder has many apertures (see figure 11). In cases where edge completion is ambiguous, or if there are several possible edge completions, surface completion may direct edge completion processes to the correct interpolation. Surface features may also interact with edge interpolation processes by making interpolation more likely for weakly relatable edges. The most important contribution of surface completion, however, is likely to be its role in perceptual unification.

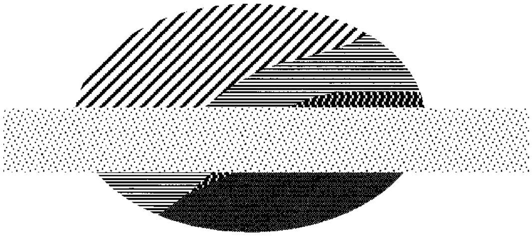

Figure 3. Edge interpolation mechanisms can by themselves produce the unified representation of an oval, despite the presence of different surface features.

1.3 *Surface and edge interactions in visual completion*

Phenomenologically, edge and surface completion processes make different contributions to the problems of perceptual unification and shape recovery. These are illustrated in figure 4 by placing an occluder in different positions in front of the same shape. In figure 4a, edge interpolation provides shape information and surface features may amodally extend within the interpolated contours. In figure 4b, the edges are not relatable, but edge *extension* processes might provide some elongation of the figure. Surface features may spread amodally within extended edges, but the specific shape of the occluded region is amorphous. In figure 4c, both edge interpolation and surface completion processes may integrate the two black fragments, because their edges are relatable and they have the same surface features. Edge interpolation should provide shape information in addition to unification. Figure 4d is identical to figure 4c except for the surface features of one fragment. While this might impede surface completion, edge relatability should still contribute to unification. Conversely, unity is produced in figure 4e solely by surface-feature similarity: the new occluder position renders the black regions nonrelatable, disabling edge interpolation. However, surface-feature similarity may integrate the partly occluded regions via spreading within each region's amodal edge extensions. Unit formation by surface completion alone would leave the shape of the occluded area vague. Finally, figure 4f is identical to figure 4e except for the surface features of one fragment. Neither edge interpolation nor surface completion processes can integrate the two fragments: The impression of two separate pieces behind the occluder should be strongest in this display.

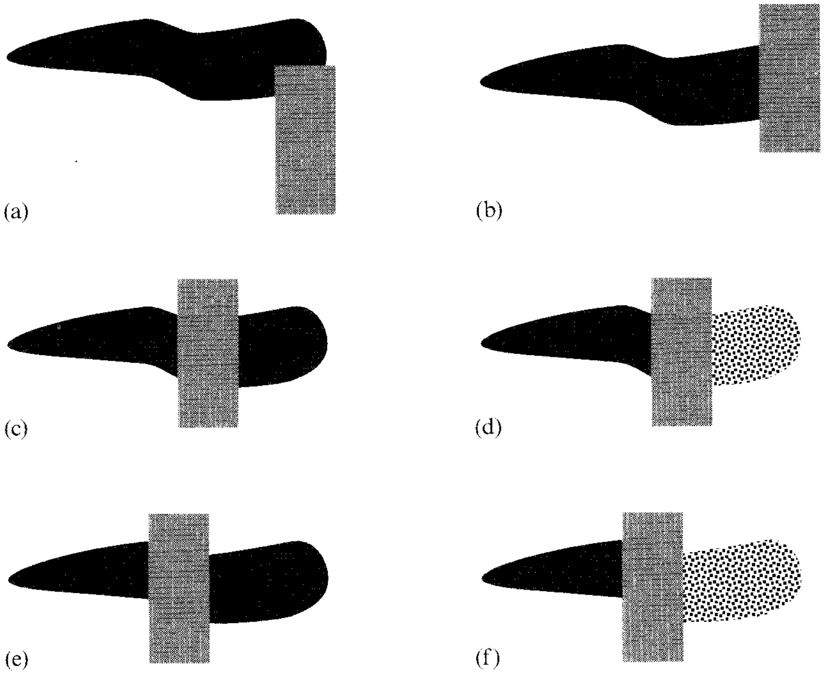

Figure 4. Edge and surface-feature completion processes make different contributions to visual completion. In (a), edges are interpolated, ie two edges connect behind the occluder, giving the occluded region a determinate shape. Surface features spread within visible and interpolated edges. In (b), edges and surface features amodally extend some distance behind the occluder, but shape is less determinate. Displays (c) – (f) involve separate partly occluded regions; visual completion affects both perceived unity and shape in these displays. In display (c), both edge interpolation and surface-feature completion contribute to perceived unity and shape. In (d), edge interpolation but not surface-feature completion contribute to perceived unity and shape. Displays (e) and (f) are identical to (c) and (d), but the occluder has been shifted to disrupt edge relatability. In (e), edge interpolation and shape recovery are disrupted, but surface-feature completion contributes to some perceived unity. In (f), neither edge interpolation nor surface-feature completion contribute to perceived unity.

There have been virtually no systematic experiments on surface-feature-based completion for partly occluded images (amodal completion) nor on its interactions with edge interpolation and edge continuation. Studies of *modal* surface completion processes, processes that bear a close link with amodal completion (Nakayama et al 1990; Kellman and Shipley 1991; Shipley and Kellman 1992a; Yamada et al 1993; Tommasi et al 1995; Ringach and Shapley 1996; Kellman et al, in press), are also unable to resolve these questions because they used stimuli in which edges may have participated in the interpolation process (van Tuijl and de Weert 1979; Metelli 1985). Every time an image fragment was modally completed, the bounding edge of that fragment was also completed, guided by the tangent discontinuities and edge relationships present in those displays. If surface-feature similarity does contribute to visual completion, that contribution is most likely overshadowed when the boundaries of those image fragments also complete, given that edge information makes a dominant contribution to completion.

2 General design of experiments

The studies reported here represent a first attempt at understanding the main features of the surface completion process. To isolate the surface process, we used stimuli in which the contribution of surface features to the visual interpolation of a target area is emphasized over that of the contribution of edge interpolation processes. We used displays in which a circular target area was centered upon a rectangle, and assessed completion between the circle and other elements in the display. We used circular target areas for two reasons. First, all points along the boundary of the circle have the same border ownership. In our stimuli, boundary ownership of the target area is ambiguous in the context of our displays, and the appearance of the circle as either a hole or a spot (see figure 3) must be determined from the other elements in the displays. Second, the absence of tangent discontinuities in the circular areas ensures that edge information does not contribute to visual completion of the circle, allowing us to isolate the effects of the surface completion process.

On the basis of phenomenological observations, we hypothesize that surface completion mechanisms (i) integrate similarly colored and similarly textured surface fragments, and (ii) operate within relatable boundaries and tangent extensions (see figure 3; cf Kellman and Shipley 1991). The two facets of this proposal—similarity of features and the position of the amodally interpolated and extended boundaries—were examined in a series of paired-comparison and classification tasks. In each of the first three experiments, we used solid black surfaces, textured surfaces, and color gradient surfaces to allow us to assess the generalizability of our results to a variety of surface features.

Participants were shown a rectangle partly occluding two bars. The circular target area placed near the center of the rectangle was colored to match or mismatch the color of the bars (the congruent and incongruent color conditions, respectively). If participants perceived the circle as a hole, we assumed they did so because surface completion mechanisms integrated the surface of the disk with the surface of the partly occluded bars; the ambiguous ownership of the boundary is clarified as belonging to the occluder. If the boundary is perceived to belong to the circular target area, then the target area is seen as a disk, or spot, on top of the rectangle. The spatial relationships of the bars were manipulated in order to see the effects of successful and unsuccessful edge interpolation on surface completion.

For these initial studies of surface completion, we wanted to assess a relatively large number of display configurations to get an overall view of the process. Accordingly, we used two tasks, a paired-comparison task and a classification task that would permit comparison of numerous displays in individual experiments. The paired-comparison data were also transformed into a psychometric interval scale, allowing us to judge the degree to which our display manipulations changed the appearance of the circle. In another line of research, not reported here, we have found evidence for the surface completion process under occlusion in a limited set of displays using an objective performance measure (Yin et al 1995, 1996).

In the paired-comparison task, subjects were shown pairs of stimuli and were asked to choose one stimulus as having a more realistic hole in the occluder (see figure 5). A stimulus that is frequently chosen over other stimuli as having a hole can be inferred to have a more realistic hole than a stimulus that is frequently rejected. A classification task was also used in order to verify whether subjects did indeed see a hole in a particular stimulus, to remove the possibility that all the stimuli had realistic holes or all had spots. In this latter task, subjects classified each display as having a "hole" or a "spot", and these data were used to anchor the psychometric scales.

Pilot studies have shown that there are benefits and disadvantages to using each of the two tasks we chose. The classification paradigm by itself may not be sensitive to small differences between stimuli, since the dependent variable is a dichotomous "hole" or "spot" response. The paired-comparison task can be more sensitive to small differences since the observers' choice between two similar displays serves to rank them. However, the paired-comparison task is heavily dependent upon the particular stimulus set used in the comparisons: two stimuli paired within a homogeneous stimulus set will yield different scale values than when they are paired within a heterogeneous stimulus set.

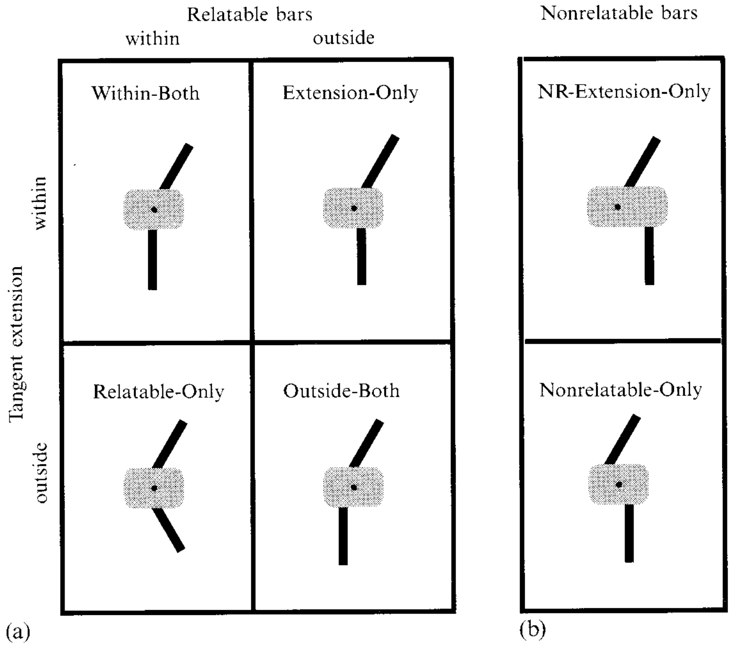

Figure 5. The relatable (a) and nonrelatable (b) bar configurations used in experiment 1; subsets of these six stimuli were used for the other experiments. The term 'bar configuration' will be used to refer to a particular combination of bar orientation and bar relatability. In (a) the 2×2 design crosses the factors of the circle position within an interpolated path with position within a tangent extension. In (b), the NR-Extension-Only display contains a circle within a tangent extension, and the Nonrelatable-Only display contains a circle within the imaginary connection of the unrelatable bars.

The similarity between stimulus items may also bias observers toward attending to particular aspects of the configurations.

This experiment addresses the homogeneity concern by interleaving trials from all three stimulus sets: the color gradient stimulus set, the solid black stimulus set, and the textured stimulus set. This also allowed a within-subjects comparison of surface spreading among these different surface features. In order to decrease cognitive influences, exposure time was limited to 3 s.

In experiment 1 we varied the *bar configurations* and examined surface completion within various relatable and nonrelatable edges and tangent extensions. In experiment 2 we examined how the relative *orientations* of the two bars affected surface completion. In experiment 3 we examined the effects of *surface similarity* on surface completion. In experiment 4 we examined surface completion of a *color gradient*, testing the hypothesis that surface completion was sensitive to the rate of change along a color gradient. In experiments 1 through 3, we also assessed the effects of the different surface-feature types. Trials from all four experiments were interleaved during a single session.(2)

2.1 *Participants*

Nineteen male and female undergraduates at the University of California, Los Angeles participated in partial fulfillment of course requirements for an introductory psychology course. Participants all had normal or corrected-to-normal vision.

(2) Owing to an equipment error, the data collected during this session that were intended to test the color-gradient interpolation hypothesis were not usable. Instead, experiment 4 provides data from an identical color-gradient experiment that was conducted with another group of participants. Relevant details will be presented later.

2.2 *Displays*

The stimuli were two-dimensional and consisted of a gray occluder (subtending 2 deg × 1.3 deg) with a bar (0.23 deg × 1.86 deg) protruding from its top and from its bottom (see figure 5). The top bar was oriented at 30° and the bottom bar was positioned vertically. A small circle (0.19 deg in diameter) was placed on the gray occluder. These dimensions were chosen so that the extended tangents of the bars and the interpolated path between the bars could be independently manipulated. We also controlled for the length and separation of the visible edges, or the *support ratio* (Shipley and Kellman 1992b; Banton and Levi 1992; Lesher and Mingolla 1993). The circle was always vertically centered upon the occluder so that it remained roughly equidistant from the bars on either side. The circle was horizontally centered upon the occluder whenever possible, so that the circle was always at least 1 deg from either vertical edge of the occluder. These stimuli were displayed upon a white background.

All three surface-feature types were used within each of the first three experiments. For the solid black displays, the bars were both colored black, as was the circle. For the textured displays, the bars were textured with a random-dot pattern. A random-dot texture was used so that the texture would have no apparent directional grain. Figure 6 shows examples of the stimuli. In order to control for possible effects due to particular patterns, the same dot pattern was used for all the circles. For the same reason, the textures on the bars were also the same, so that same low-level features were adjacent to the occluder for all bars of a particular orientation. For the color-gradient displays, the bars were constructed so that a red-to-yellow gradient would appear along the length of the completed bars, with the gray rectangle occluding the orange gradients. In experiments 1 and 2, the circle was always colored orange, which correctly matched the interpolated color gradient; circle color changes made for the other experiments are described later.

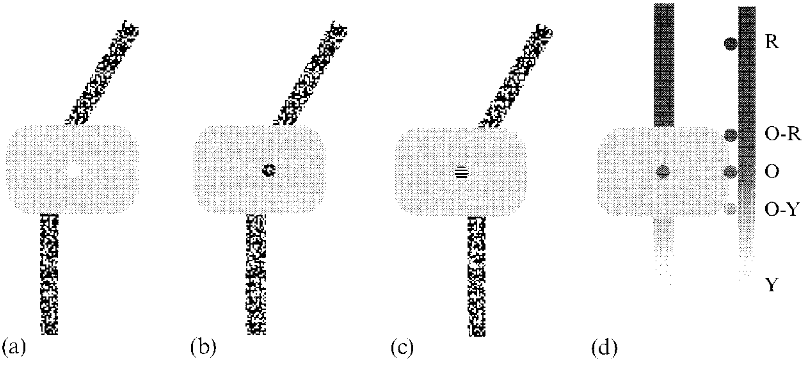

Figure 6. Examples of the textured and color-gradient stimuli used in these experiments: (a) a background-congruent, Outside-Both display; (b) a congruent, Within-Both display; (c) an incongruent, Extension-Only display; and (d) a color-gradient display. The five small circles alongside the gradient show the portions of the gradient used for the circle colors: R, red; O-R, orange-red; O, orange; O-Y, orange-yellow; Y, yellow.

2.3 *Procedure and apparatus*

Subjects responded to all 390 trials within a 1 h session. Stimulus presentation and data collection were controlled by MacProbe (Hunt 1994), run on an Apple Macintosh IIfx with an E-machines 21-inch monitor. Subjects were seated approximately 1 m from the screen.

2.3.1 *Paired-comparison task.* Subjects were given the following instructions:

> "In this experiment, you will be shown displays, each of which has a small round area. In some displays, this round area may look like an object, or SPOT, in front of a gray surface; in other displays, this round area may look like a HOLE in the gray surface through which you can see part of another surface. On each trial, you will be shown two displays

> simultaneously, each having a small, round area. Your task is to decide in which of the two displays the round area looks more like a realistic HOLE. There may be some trials where it seems very obvious; on other trials, it may be more difficult, either because both round areas look like holes, or both look like objects. Even where there is not much of a difference, pick the display in which the round area looks more like a realistic hole."

The two examples accompanying the instructions consisted of two large rectangles, each with a circle at the bottom right-hand corner. Jutting out from the same corner was a smaller rectangle that was the same color as the circle in one example and a different color in the other. The occluding rectangles were colored with a yellow-to-red color gradient. Participants were asked to select the example that looked more like it had a hole, which they were generally able to do without difficulty.

Participants were also told that there might be one or more bars behind the gray occluder, but that the *width* of the bars would not change. The side of presentation for each stimulus pair was randomly determined. Participants were told to press a key labeled "L" when they chose the left-hand display, and the key labeled "R" for the right-hand display. Participants initiated each trial; stimulus pairs were presented randomly and remained on the screen until the participants' response, or until 3 s expired.

Participants were given repeated practice with one trial to ensure they understood the 3 s response deadline. Two small asterisks were vertically aligned on the monitor between the two stimulus displays. One asterisk disappeared with each passing second, and the entire stimulus display disappeared after 3 s. At that time, if the participant had not responded, a continuous beep was emitted by the computer until a late response was entered. If the participant responded before the deadline, the entire display was immediately removed and the trial ended. No data were excluded if a particpant took longer than 3 s to respond. However, the beep encouraged participants to respond quickly, so that all responses were collected within 4 s.

2.3.2 *Classification.* At the conclusion of the experiment, each stimulus item was presented individually and in random order on the screen. Participants were asked to press the "H" key if the circle in each display looked like a hole, and "D" if it looked like a dot. These classification data were used to anchor the psychometric scale values, and the classification means will be given for each experiment. These data were also analyzed with an ANOVA, but the results were not qualitatively different from the paired-comparison data. Because these classification data might be less sensitive to finer differences between stimuli, as discussed earlier, we will not report most of these statistics. We will only report the classification findings regarding the comparison of surface features. Because our stimuli were not paired across different surface features, the paired-comparison data cannot be used to test for effects due to different surface-feature types.

A total of 300 trials were constructed for the experiments 1 through 3, and 105 trials were constructed for experiment 4. 15 of these trials were represented twice across all the experiments and thus were removed, yielding 390 different trials. The data from the shared trials were applied to as many analyses as were appropriate.

2.3.3 *Data analysis.* Subjects' paired-comparison data were converted into a psychometric interval scale via Thurstone's method of scaling, Case V (Gescheider 1985). In such a scale, stimuli with similar perceptual magnitudes of the scaled attribute have similar values. In our data, the scaled attribute was "hole-ness"; positive values(3) indicate a tendency to choose that item as having a hole, while negative values indicate a tendency to reject that item as having a hole (ie the tendency to choose the other item of the pair presented). Values near zero indicate equal probability of choosing or rejecting that item.

(3) Because this is an interval scale, there is no true zero point. Usually a constant is added to each value to yield a scale with all positive values. We did not do this because the zero point on these scales corresponded to an equal preference for either of the items being compared; positive and negative values nicely illustrate the direction of preference.

3 Experiment 1: Bar configurations

In experiment 1 we tested the hypothesis that surface completion is successful only within relatable borders or tangent extensions of the borders. We designed six displays in which the relatability of the two bars and the position of the circle were varied.

3.1 *Design*

Three aspects of the stimuli were manipulated in the design (see figure 5). One variable concerned the relatability of the bars. Two variables concerned the position of the circle relative to the *tangent extensions* of the bars, and relative to the *path* between the two bars.

In the relatable bar configurations, the interpolated path was a circular arc whose ends were tangent to the top and bottom bars. The positioning of the circle within or outside the path was fully crossed with its positioning within or outside the tangent extension, yielding four stimuli: Within-Both, where the circle was placed within the interpolated path, which coincided with the extended tangents; Outside-Both, where the circle was placed outside of both the interpolated path and the tangent extensions; Extension-Only, where the circle was placed outside of the interpolated path but within one tangent extension; and Relatable-Only. The Relatable-Only configuration was designed by taking the Within-Both configuration and rotating the bottom bar counterclockwise by 30° (see figure 5a). The circle was placed within the interpolated path, but outside of the tangent extensions.

For the nonrelatable displays, the top bar of the Within-Both configuration (see figure 5a) was shifted by 0.7 deg to the left so that the two bars were no longer relatable (figure 5b). According to the relatability criterion there was no interpolated path since the path would have to be doubly inflected. Instead, we used the straight-line connection of the nonrelatable bars (between the points where each bar is occluded) to position the circle. Of the possible nonrelatable bar configurations, we included only the Nonrelatable-Only displays, in which the circle was placed within the connection of the nonrelatable bars, and the Nonrelatable-Extension-Only displays (hereafter, 'NR-Extension-Only'), where the circle was placed within the tangent extension of a nonrelatable (hence the 'NR') bar. The latter display was included to see whether the relatability of the bars affected the observer's willingness to complete a circle with a tangent extension.

3.2 *Results and discussion*

The data from the paired-comparison tasks showed that the six bar configurations fell into three categories, as can be seen in figure 7: the Within-Both and Relatable-Only configurations were consistently judged as having the most realistic holes (highest psychometric scale values); the Outside-Both configuration was consistently judged as having the least realistic hole (lowest scale values); and the remaining Nonrelatable-Only, Extension-Only, and NR-Extension-Only displays had moderately unrealistic holes (small, negative values), eliciting both hole and spot judgments.

Figure 7 also lists the Kendall coefficient of agreement u for paired-comparison data, indicating the extent of agreement between the observers' judgments (Siegel and Castellan 1988). This nonparametric statistic can be considered to be similar to the Spearman rank-order correlation coefficient, r_s, with +1 indicating maximum agreement between observers, but with $-1/(\text{number of observers})$ indicating maximum disagreement between observers. The u approximates the χ^2 distribution in our studies, and the value of each u is also presented in figure 7. All us indicate a moderate and significant agreement between observers, with $p < 0.0001$ in all cases.

The classification data were used to anchor the psychometric scale, and showed that across all surface features, a mean of 96.5% (0.04 standard deviation) of the observers saw the Within-Both display as having a hole, but only 26.3% (0.10) saw the Outside-Both

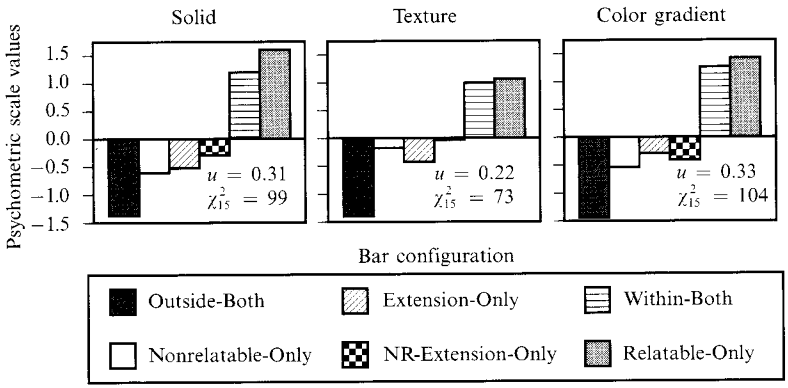

Figure 7. The psychometric scales for the six matching-circle bar configurations in the solid, textured, and color-gradient stimuli. See text for an explanation of the accompanying statistics.

as having a hole. This verifies that our stimuli successfully covered the span of realistic holes and spots, and that the values of the psychometric scale can be assumed to correspond to this range of percepts. An omnibus ANOVA on the classification data in this experiment revealed no main effects nor interactions due to surface features.

The results show that circles in the interpolated path of relatable edge configurations (Within-Both and Relatable-Only) were perceived as being the most realistic holes, while circles that lie only within a tangent extension (Extension-Only and NR-Extension-Only) were perceived as moderately poor holes. This is consistent with the hypothesis that surface completion is successful within relatable borders and tangent extensions. There were two displays in which the circle was positioned outside of relatable borders and extensions: the Outside-Both and Nonrelatable-Only. Observers perceived the Outside-Both configuration as having the least realistic hole of all the displays, which was consistent with our hypothesis. However, the circle in the Nonrelatable-Only configuration was perceived to be equivalent to circles positioned only within an extension. This suggests that surface completion processes may assist path interpolation in cases where the edges are nonrelatable. We will discuss this further in section 8.

4 Experiment 2: Bar orientation

Relatability, for these stimuli, is a combination of the relative orientations of the inducing edges and of the horizontal spacing of the closer ends of those edges. While the horizontal-spacing parameter tolerates very little misalignment (approximately 15 min arc; Kellman and Shipley 1991), the relative orientation parameter should tolerate angular disparities up to 90°. Within that range, however, the strength of edge interpolation should decrease as disparity increases.

In experiment 2 we tested the hypothesis that the relative orientations of the two bars would have an effect on the strength of the interpolated path. Surface completion might be easier with a strongly interpolated path, leading to a stronger preference for circles within the more collinear paths over circles within less collinear paths. In experiment 2 the bar orientations of the Within-Both, Outside-Both, and Nonrelatable-Only configurations were varied. In the Outside-Both configurations, the inability to complete the circle with the bars might be made clearer when the interpolated path is stronger. The Nonrelatable-Only configurations were included as controls.

4.1 *Design*

In the Within-Both, Outside-Both, and the Nonrelatable-Only displays, the top black bars were oriented so that they were collinear with the bottom bar (0°), rotated 30°, or rotated 60° clockwise from vertical (see figure 8a). This orientation will be suffixed to the display type (eg Within-Both.30°). The bar below the occluder was always vertical. The Extension-Only and Relatable-Only displays were not included because in the collinear bar orientation, any circle placed within an extension must also be placed within the path that is interpolated between the relatable edges. We included the Nonrelatable-Only configuration partly to provide a control condition. This second experiment shared two stimuli with the first experiment, the Outside-Both.30° and the Within-Both.30° displays. Paired comparisons were only made within other stimuli of the same bar configuration type (eg between the 0°, 30°, and 60° versions of the Within-Both type), yielding a total of 27 trials across all surface-feature types.

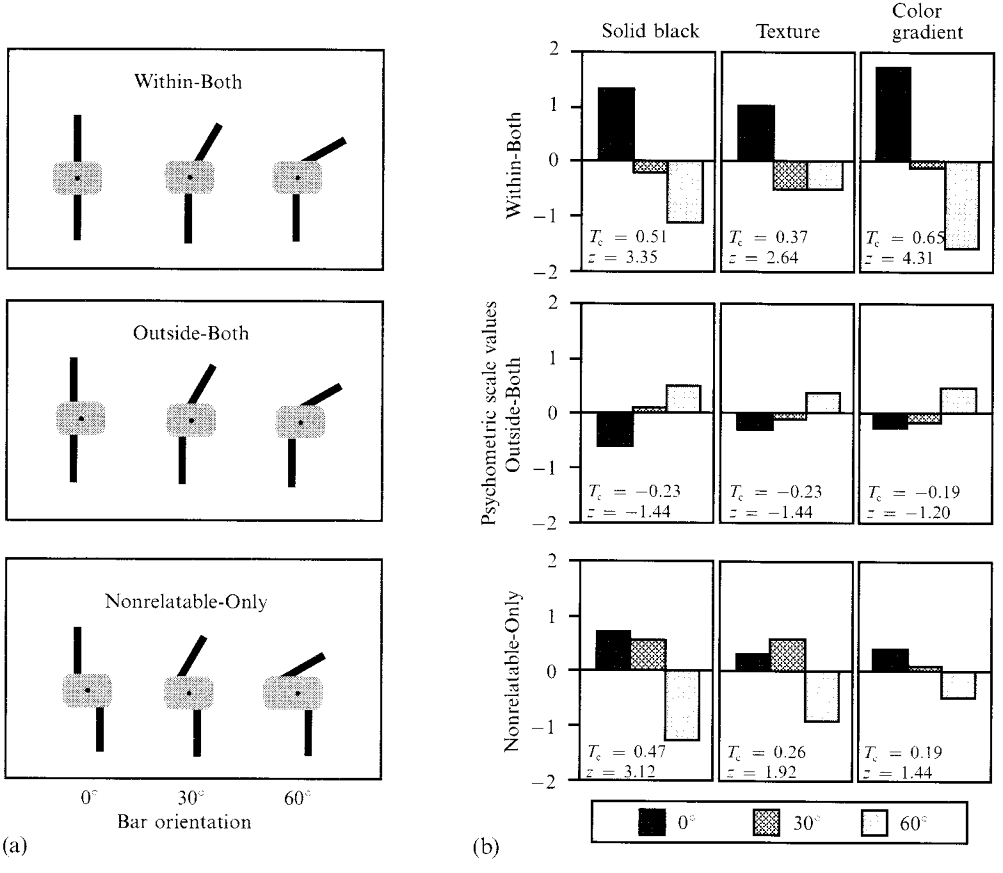

Figure 8. (a) The stimuli from experiment 2. (b) Results showing the effect of bar orientation on surface completion. The psychometric scales for the Within-Both, Outside-Both, and the Nonrelatable-Only configurations for each surface-feature type show that the orientation of the bars has the most consistent effect on the Within-Both configurations, and a less consistent effect on the Nonrelatable-Only configurations. Included in the graph are the T_c statistics and z score assessing degree and significance to which the data show an observer's preference for the collinear over the less collinear stimuli.

4.2 *Results and discussion*

The paired-comparison data showed that there was a significant preference for collinearity for the Within-Both configurations of all surface features, and for the Nonrelatable-Only configurations of only the solid and textured surface features. Figure 8b shows the psychometric scales for each bar configuration by surface-feature condition. Nonparametric statistics were conducted on the paired-comparison data to determine the correlation between the observer's preferences and a criterion preference. The measure we used was the T_c, which is the average of the Kendall rank-order correlations (T)

between each observer and a criterion ranking (Siegel and Castellan 1988).(4) The ranking we used as the criterion was the preference of the more collinear bar orientations over the less collinear bar orientations (specifically, 0° > 30° > 60°). Figure 8b also shows the T_c for each of these cells, along with the z score that we calculated from the T_c values. We also calculated the Kendall coefficient of agreement u, but in each analysis where there was a significant agreement (u) among observers there was also a significant agreement with our hypothesized ranking of preferences (T_c). In experiment 2, and in subsequent experiments, u is subsumed by T_c: we used T_c to test for a specific, theoretically-motivated pattern of preferences, and u to test for observer agreement in the cases where our hypotheses do not present a clear rank-ordering of preferences among the stimuli.

For the Within-Both displays, the T_c statistic showed that across all surface features the collinear Within-Both configuration was preferred over the less collinear bar orientations. This collinearity preference actually has three components: 0° > 30°, 30° > 60°, and 0° > 60°, but the data need not support all three components in order to find a significant T_c. A posteriori t-tests on each component showed that the 0° > 30° and 0° > 60° components were all significant, but that the preference of 30° over 60° was significant only for the color gradient condition ($t_{18} = 5.46$, $p < 0.0001$).

The Nonrelatable-Only configurations also elicited the same order of preference (0° > 30° > 60°), but this was significant only for the solid and textured surface features. The psychometric scale also shows that the 0° and 30° configurations did not differ from one another.

For the Outside-Both displays, the data show a nonsignificant, *reversed* preference for the less collinear configurations over the more collinear configurations. This might indicate that the stronger the interpolated path is, the easier it is for observers to judge whether a surface fragment lies within the interpolated boundary.

The Within-Both and Nonrelatable-Only data support the idea that there are categorical boundaries in the perceptual system (Foster 1983; Foster and Ferraro 1989). For the Within-Both configurations, all non-collinear (but still relatable) configurations might fall within the same category, resulting in similar scale values. There might also be a similar categorical boundary affecting the judgments of the Nonrelatable-Only configuration, but these suggestions need to be tested further.

The classification data verified that these stimuli elicited both realistic hole and spot percepts. Across all surface types, the mean percentages of observers making a "hole" classification were: 25.6% (SD 11.3%) for the Outside-Both stimuli; 67.3% (SD 9.8%) for the Nonrelatable-Only stimuli; and 95.3% (SD 3.2%) for the Within-Both stimuli. An omnibus ANOVA on the classification data in this experiment revealed no main effects nor interactions due to surface features, suggesting that the effects reported here could be generalized to all surface-feature types.

To summarize, these results suggest that surface completion shows some sensitivity to the strength of the interpolated boundaries, which we manipulated by varying the relative orientations of the two bars. This sensitivity is strongest with the Within-Both displays. Although the Outside-Both displays show little sensitivity to the strength of the interpolated edges, the pattern of results is still consistent with a preference for displays with more collinear edges. In the Nonrelatable-Only displays, the sensitivity to edge relationships may reflect an interaction of the surface completion process with the individual amodal extensions of each visible edge, and will be further discussed in section 7.1.

(4) The value of T varies from $+1$ to -1, and is related to the Spearman rank-order correlation coefficient; accordingly, negative T_c values indicate a reversed preference. The preference rankings of the stimulus items can be determined from the paired-comparison data. With large (> 10) numbers of stimulus items, the distribution of T approximates the normal distribution, and thus may be tested for significance (Siegel and Castellan 1988).

5 Experiment 3: Surface congruence

In experiment 3 we tested the hypothesis that surface completion operates upon surfaces with congruent features. We examined surface congruence with solid black surfaces, color-gradient surfaces, and textured surfaces, each described earlier. Congruence was manipulated by changing the color of the circle.(5) Congruent circles should be seen as holes when their surface features match those of the bars, and when the circle is positioned between relatable bars. The background-congruent circle should successfully complete with the background, but only if it is outside of the path between relatable bars. Incongruent circles should be seen as spots.

5.1 *Design and stimuli*

In a 4 × 3 × 3 design, the 30° bar orientation versions of the Within-Both, Outside-Both, Extension-Only, and Nonrelatable-Only configurations were presented in the three different surface-congruence conditions: congruent-feature, where the circle and bar colors matched; incongruent-feature, where circle and bar colors did not match; and background-congruent, where the circle matched the color of the background (white). These conditions were crossed with the three surface-feature types. The incongruent stimuli were new to this experiment. For the solid black bars, the incongruent circle was colored green. For the textured bars, the incongruent circle was a texture of fine horizontal lines. For the color-gradient bars, the incongruent circle was the same yellow as that used to represent the bottom-most portion of the color gradient. Four of the six stimuli from experiment 1 are represented in the design of this experiment. Therefore, we added the other two stimuli from experiment 1 to the twelve stimuli in this experiment and paired the resulting fourteen stimuli. These stimuli were paired only within each surface-feature type, yielding 273 combinations.

5.2 *Results and discussion*

Figure 9 shows two clear effects: The incongruent circles tended to be preferred as "spots" across all configurations. The matching circles tended not to elicit strong preferences except for the Within-Both configuration, where the matching circle elicited the strongest "hole" preference. For the Outside-Both configurations, the background circle provided the most realistic hole compared with the other circles, supporting our predictions. However, this preference was still considered weak relative to that for the matching circle Within-Both display.

The Kendall's u statistics indicated that observer agreement was highest for the matching-color circles in all surface-feature conditions (see figure 9). The incongruent circles elicited consistent observer agreement in the texture and color-gradient conditions, but not the solid condition. The background circle only elicited a marginal agreement, and only for the solid condition.

The incongruent circles were poor holes, except in the Within-Both configuration with the color-gradient stimuli. This pattern of results was confirmed in the classification data: Although there was no overall interaction, there was a marginal simple effect of the incongruent circle in the gradient stimuli ($F_{3,54} = 2.75$, MSE $= 0.13$, $p = 0.05$). The probabilities of being classified as "hole" were 0.16 for the Outside-Both, 0.21 for the Extension-Only, 0.26 for the Nonrelatable-Only, and 0.47 for the Within-Both configuration. A contrast showed that the incongruent Within-Both configuration had a significantly higher probability of hole classification than all the other incongruent-circle configurations ($F_{1,18} = 9.2$, MSE $= 0.11$, $p = 0.007$).

The classification data also verified that observers saw both realistic holes and spots. For each scale, the stimuli with the highest and lowest psychometric values were the congruent Within-Both stimulus and the incongruent Outside-Both stimulus, respectively.

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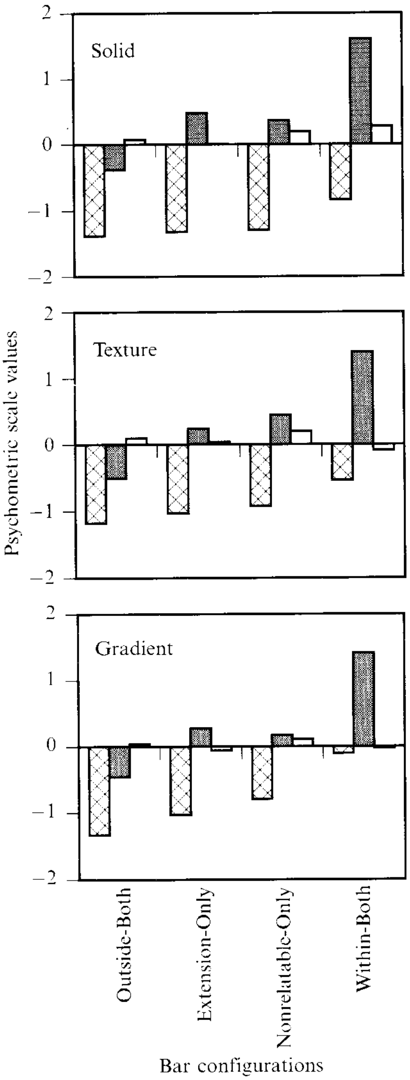
(5) An earlier study (Yin et al 1995) showed similar effects when the bar color was changed instead of the circle color.



	u	χ^2_6	p
☒ Incongruent	0.01	6.63	0.35
▨ Matching	0.37	46.21	< 0.0001
☐ Background	0.06	12.11	0.06

	u	χ^2_6	p
☒ Incongruent	0.12	18.42	0.005
▨ Matching	0.26	33.58	< 0.0001
☐ Background	−0.04	2.00	0.91

	u	χ^2_6	p
☒ Incongruent	0.22	30.21	< 0.0001
▨ Matching	0.37	46.21	< 0.0001
☐ Background	−0.03	2.42	0.88

Figure 9. The three graphs show the psychometric scales of the Outside-Both, Extension-Only, Nonrelatable-Only, and Within-Both configurations when the congruence between the circle characteristics and the other components of the display was varied. Scale values are only comparable within each surface-feature cell.

The percentage of people reporting "hole" for the Within-Both and Outside-Both stimuli were 100% and 5.3% (respectively) for the solid black stimuli, 94.7% and 5.3% for the texture stimuli, and 94.7% and 15.8% for the color-gradient stimuli. It may be that the luminance of the yellow (incongruent) circle was similar enough to the white background to cause some confusion to the observers: both the yellow circle and the background circle displays had similar scale values.

To test the surface-feature hypothesis, a 3 (surface type) × 3 (surface congruence) × 4 (bar configuration) ANOVA on the classification data revealed a main effect of surface-feature type ($F_{2,36} = 4.06$, $\mathrm{MSE} = 0.15$, $p = 0.025$), but no interactions with surface-feature type. The main effect of surface feature was due to the higher probability of "hole" classification for color-gradient stimuli ($M = 0.539$) than for both solid ($M = 0.439$) and texture ($M = 0.465$) stimuli combined ($F_{1,18} = 4.16$, $\mathrm{MSE} = 0.08$, $p = 0.0012$), with no higher-order interactions.

The results show that across different surface features, the best holes were produced by a matching circle between the interpolated path between relatable edges and by a background circle outside of that path. The best spots were produced by circles of incongruent features. Matching circles and background circles within a tangent extension and between nonrelatable bars supported hole percepts equally well as spot percepts. These findings supported the predicted operation of surface completion. Effects of surface features, as measured by the classification data, did not interact with any other variable in any experiment, which suggests that the effects we report here can be generalized across different surface features.

6 Experiment 4: Color-gradient interpolation

Color and texture gradients are of interest because they provide important information about the shape and local depth information of surfaces. In order to interpolate a gradient, however, the rate of change of the gradient might also need to be interpolated. In this experiment, observers had to choose the most realistic circle out of five different circle colors. In addition to the 'correct' orange, there were easily discriminable (and thus easily rejected) red and yellow circles, as well as less discriminable orange-yellow and orange-red circles. If observers do not interpolate the red-yellow gradient smoothly during surface completion, they might not prefer the correct orange circles over the orange-yellow and orange-red circles.

6.1 *Method*

6.1.1 *Participants.* Participants were seventeen male and female undergraduates from the pool described above. None had participated previously.

6.1.2 *Design.* In the 5 × 3 color-gradient experiment circle, color was varied at five levels (see figure 6d) and bar configuration at three levels: Within-Both, Outside-Both, and Extension-Only. The gradient was created by blending red and yellow on a color palette in Canvas 3.5 (Deneba Software, Miami, FL). Five circle colors were chosen. One was an unambiguous red, another was an unambiguous yellow. The third was the orange that correctly matched the interpolated red-yellow gradient. The fourth and fifth were also orange, but were oranges chosen from the last visible orange leading into the occluder from the top (orange-red) and the first visible orange leading out of the occluder toward the bottom (orange-yellow). The resulting fifteen stimuli in this design were paired, yielding 105 combinations.

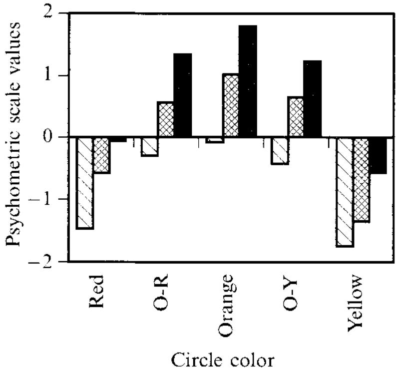
6.1.3 *Procedure and apparatus.* The stimuli were displayed on a Mitsubishi Diamond 20-inch monitor. Observers were allowed unlimited viewing of the stimuli but were asked to respond as quickly and as accurately as possible. The grand mean response time of the observers in this experiment was 2396 ms, with a standard deviation of 1020 ms. All other aspects of the apparatus and procedure were identical to those of the previous experiments.

6.2 *Results and discussion*

In the color-gradient displays, subjects tended to report seeing a hole when the circle color corresponded to the color of the interpolated gradient (orange). This suggests that surface completion processes can interpolate not only a constant color, but also a gradient color.

The paired-comparison data were psychometrically scaled, and are presented in figure 10. There was a significant preference of orange over red (orange > orange-red > red) for all configurations, with a mean $T_c = 0.57$. There was also a significant preference of orange over yellow (orange > orange-yellow > yellow) for all configurations, with their mean $T_c = 0.70$. All T_cs and significance tests are presented in figure 10. The Kendall coefficient of agreement u was 0.39, showing a moderate and significant agreement between observers ($\chi^2_{105} = 756.35$, $p < 0.0001$). t-Tests were used to test the components of each preference, and confirmed the preference of orange over orange-yellow (bottom bar) for all configurations (t_{16} = 2.38, 2.13, and 2.13 for the Within-Both, Outside-Both, and the Extension-Only displays, respectively; all $ps < 0.05$), and of orange over orange-red (top bar) for only the Within-Both configuration (t_{16} = 3.11, 0, and 1.46 for the Within-Both, Outside-Both, and Extension-Only displays, respectively). These data suggest that a color-gradient surface can be interpolated in the Within-Both configuration, as shown by the significant preference of orange over both orange-red and orange-yellow. For the other configurations, the overall significant preference for orange over the other colors suggests that color gradients can also be interpolated in those configurations, although this needs to be replicated with precisely controlled colors and color gradients.

The classification data confirm that the psychometric scale contains both realistic holes and spots. The red Outside-Both stimulus contained the least realistic hole, being classified as "hole" by only 10.5% of observers, and the orange and orange-red Within-Both stimuli had the most realistic hole, as classified by 94.7% of the observers. The classification data do disagree slightly with the psychometric scale on which color provided the most realistic hole percept, but, as mentioned earlier, the psychometric scale is likely to be more sensitive to differences between preferences.



	Orange > Yellow		Orange > Red	
	T_c	z	T_c	z
■ Within-Both	0.69	4.56	0.71	4.69
▨ Extension-Only	0.73	4.81	0.51	3.42
▧ Outside-Both	0.67	4.43	0.49	3.29

Figure 10. The preference for the best-matching orange over the other colors as the most realistic hole.

7 General discussion

The predicted relationship between amodal surface completion and edge relatability was that surface completion would integrate similarly featured surface fragments, and operate within edges interpolated according to the relatability criterion. The results from this series of experiments generally supported this hypothesis, and yielded some unexpected findings that may allow us to understand more clearly how edges and surfaces interact.

Amodal surface completion operates on a variety of different surface features, and is highly sensitive to the similarity of the surface features. Observers generally perceived the incongruently-colored circles as spots on the occluder (experiment 3). Amodal surface completion also was sensitive to the presence of relatable edges. Subjects chose the Within-Both configuration as the most realistic hole, and chose the Outside-Both configuration as the least realistic (experiment 1). Results from these experiments also suggest that observers were sensitive to the relative orientations of the two bars, within the ranges used in these experiments (experiment 2).

7.1 *Interpolating paths between nonrelatable edges*

The relatability criterion predicts that the Nonrelatable-Only configuration would not be unified because the edges are not relatable. Relatable edges possess a single inflection in the interpolated area. Edge interpolation in the Nonrelatable-Only configuration would require two inflections. However, observers in these experiments seemed willing to complete edges in the Nonrelatable-Only configuration, to some minor extent. When the surface features of the circle matched those of the bars, subjects tended to report the Nonrelatable-Only configuration as supporting a hole better than in the case of a mismatch. The Nonrelatable-Only configuration was also affected by bar orientation, which suggests that path interpolation in this configuration is in some way similar to the interpolation for relatable edges. There are three possible explanations for this result. The first is that the visual system may indeed be willing to doubly inflect an interpolated path. This is unlikely, given earlier findings that observers do not perceive unity between two bars in a configuration identical to the one we used here (Kellman and Shipley 1991). The second explanation is that edges are not interpolated in the Nonrelatable-Only configuration, and the hole percept arises solely on the basis of surface spreading of features between the physically specified edges. The issue of whether edges are amodally extended or interpolated in our paradigm remains to be directly tested. The third explanation is that surface completion might alter relatability constraints and be able to deflect weakly interpolated paths or amodal extensions.

It is likely that determination of the unity of a surface may precede the determination of its shape. Trick and Enns (1997) have shown that detecting of clusters of four dots precedes the determination of the global shape of the dots (either diamond or square), which suggests that unification precedes shape perception. If this is also the case with surface-fragment stimuli, surface completion may play an earlier role in perception than is currently understood: the studies we report here show that unity can be determined via surface-feature processes, in addition to the previously studied edge processes. However, as we pointed out with figure 4, unity information from surface completion may override unity information from edge interpolation. The phenomenal appearance of figures 11a and 11b suggests that when a fragment of an occluded figure is shifted so that the edges are no longer relatable, there is most likely a spatial range in which the unity of the occluded object is still present, maintained by surface completion processes sensitive to the surface similarity of the fragments.

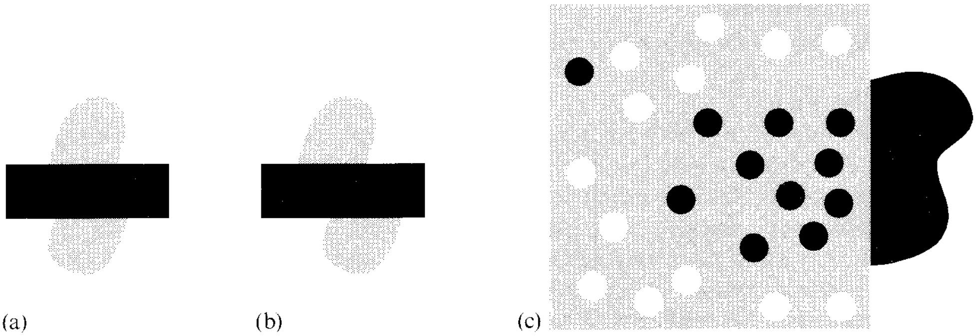


Figure 11. Display (a) shows that a slight misalignment of image fragments can destroy edge relatability and yet not completely remove the impression of unity between the two gray fragments. Increasing the misalignment (b) decreases the impression of unity. Display (c) shows a case where surface completion processes amodally extend the occluded region. However, the black circle at the top left side of the occluder is not integrated.

If unity is first established through surface completion mechanisms, then the edge completion mechanisms may incorporate multiple inflections to describe the amodal shape of the unified figure. It is most likely that multiply inflected edges are weaker than singly inflected edges.

The finding that holes are seen in the Nonrelatable-Only configuration might reveal how surface completion can alter edge interpolation and extension. When the image contains ambiguously bounded surface fragments, the surface completion process may reroute the path of extension, but only as much as is necessary to integrate the surface fragments within the edges of the object. As figure 11c shows, however, if edges are rerouted by surface completion, they are subject to constraints on the number of inflections possible: the black circle at the top of the figure does not appear to be as convincing a hole as the other black circles. The rules constraining these surface-feature and edge interactions are likely to be sensitive to a particular way of implementing relatability. In this conceptualization, each amodal edge extension has a range of possible 'deflections' that are only triggered by the presence of a matching surface fragment, with completion along a tangent extension being preferred over completion with more sharply curved extensions. Studies are currently under way to examine this range of possible deflections. The caveat remains, however, that further studies in this area need to test shape processes as well as visual integration processes.

7.2 *Edge interpolation via curvature constraint*

Takeichi et al (1995) have proposed a model of edge interpolation in which the interpolated edge may contain two inflections. The curvature constraint theory describes edge interpolation *after* unit formation has been achieved rather than as a process contributing to the formation of the unit via edge completion. According to this model, each edge that feeds into a T-junction is a possible candidate for interpolation. The path of the continued edges is constrained by the sign of the continued line. The most likely interpolation is the path that has the fewest inflections along its course. The curvature constraint theory may be useful in further studies on the role of surface completion in shape perception, under the assumption that surface completion aids perceptual unification and that unification precedes amodal shape completion.

7.3 *The representation of amodal surfaces*

Responses to the color-gradient stimuli in the classification task were intriguing. Subjects saw the best holes in the Within-Both displays where the color of the circle perfectly matched the orange of the interpolated gradient. This would suggest that although the color-gradient surface was occluded (amodal), the gradient features of that surface were represented in the amodally interpolated area. However, while the current data are consistent with the hypothesis that a rate of change was interpolated, observers need not have interpolated the rate of change of the gradient through the amodal region. Instead, observers may have performed some sort of averaging of the hues that were visible to either side of the occluder. Even though an averaging account still allows for the possibility that the amodal region also carries information about the interpolated gradient, stronger evidence for the representation of features in an amodal area needs to be found.

8 Conclusions

The studies reported here suggest that surface completion operates on similar surface fragments and that it operates within interpolated edges. The results also suggest that surface completion processes may influence the interpolation of edges (although the caveat mentioned above applies), and have implications for understanding the interaction between edge and surface completion processes. Encouraging evidence was also found for the proposal that the surface features are represented at occluded locations as a result of surface completion.

Some of the more difficult issues about the nature of surface representation remain to be addressed. They include determining whether perceptual unification of fragmented surfaces precedes shape determination or is determined in parallel, and understanding the interactions between surface and edge processes during each stage of these processes. Another issue is how surface completion under occlusion relates to filling-in processes in unoccluded displays (Yarbus 1967; van Tuijl 1975; Redies and Spillmann 1981; Paradiso and Nakayama 1991; Nerger et al 1993). Do the same mechanisms that are involved in modal surface completion in illusory contour, transparency, and retinally stabilized displays produce representations of surface features for partly occluded regions? We do not yet know. We hope that the present experiments and some new questions they provoke ultimately contribute to a clearer understanding of the representations, processes, and mechanisms involved in seeing an integrated world.

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