Journal of Experimental Psychology:
Human Perception and Performance
2003, Vol. 29, No. 6, 1211–1227

0096-1523/03/$12.00 DOI: 10.1037/0096-1523.29.6.1211

Temporal Variations in Visual Completion: A Reflection of Spatial Limits?

Sharon E. Guttman
University of California, Los Angeles

Allison B. Sekuler
McMaster University

Philip J. Kellman
University of California, Los Angeles

The completion of partly occluded objects appears instantaneous and effortless, but empirically takes measurable time. The current study investigates how amount of occlusion affects the time course and mechanisms of visual completion. Experiment 1 used a primed-matching paradigm to determine completion times for objects occluded by various amounts. Experiments 2 and 3 used a dot-localization paradigm to probe completed contour representations for a qualitative shift above some spatial limit. The results demonstrate that time to completion rises with amount of occlusion. Nonetheless, the visual system can complete highly occluded objects, even when the occlusion renders visible contours nonrelatable. Furthermore, prolonged completion times for highly occluded objects do not result from a breakdown of low-level interpolation processes: The same contour completion mechanism operates on objects occluded by different spatial extents.

The perception of objects is critical to one's interpretation of the world. However, many of the objects that a person perceives are not fully specified by visual information because those objects occlude parts of themselves or are occluded by neighboring objects. Despite the pervasive nature of occlusion, difficulties in object recognition rarely arise from incomplete visual stimulation. Somehow, the visual system seems to "complete" partly occluded contours and surfaces, resulting in the perception of meaningful, 3-D objects. Indeed, interpolated contours and surfaces arguably play as great a role in object perception as physically specified information. Thus, investigations of occlusion and interpolation are critical to the understanding of visual perception.

Numerous studies indicate that the visual system ultimately represents partly occluded objects as completed forms (e.g., Behrmann, Zemel, & Mozer, 1998; Davis & Driver, 1998; Gerbino & Salmaso, 1987; Gold, Murray, Bennett, & Sekuler, 2000; He & Nakayama, 1992, 1994a, 1994b; Moore, Yantis, & Vaughan, 1998; Pratt & Sekuler, 2001; Rensink & Enns, 1998; Sekuler, 1994; Sekuler & Palmer, 1992; Sekuler, Palmer, & Flynn, 1994; see also Sekuler & Murray, 2001, for a recent review). However, despite the phenomenological experience of visual completion as instantaneous and effortless, research also indicates that completion takes measurable time (Murray, Sekuler, & Bennett, 2001; Ringach & Shapley, 1996; Sekuler & Palmer, 1992). For example, Sekuler and Palmer found that the visual system requires 100–200 ms of processing time before the representations of objects with 25.0% contour occlusion correspond to completed forms. Ringach and Shapley arrived at a similar estimate for completion time despite using a different technique and stimulus set.

More recently, different estimates for time to completion have begun to emerge. Murray et al. (2001) suggested that the completion of partly occluded objects could occur in less than 100 ms for their stimuli and task. Bruno, Bertamini, and Domini (1997) found data consistent with the idea that time to completion decreases when stimulus displays contain stereo cues congruent with the perceived depth ordering of the target and occluder, as compared with equivalent 2-D displays. The existence of these variations strongly suggests that the time required for visual completion is not fixed within the visual system. Instead, time to completion probably fluctuates with a number of factors, including task requirements, individual differences, and stimulus variables.

In the current study, we explore how visual completion processes depend on one particular stimulus attribute: amount of occlusion. Previous studies investigating this factor have suggested that time to completion increases with the size of the occluded region (Rauschenberger & Yantis, 2001; Shore & Enns, 1997). Here, we address two issues arising from this work. First, we seek evidence that confirms the generality of this finding, which we refer to as the *temporal variation hypothesis*. Specifically, we ask whether highly occluded objects simply take longer to complete than objects occluded by lesser amounts or whether they exceed the completion abilities of the visual system altogether. Second, we ask *why* time to completion increases with the amount of

Sharon E. Guttman and Philip J. Kellman, Department of Psychology, University of California, Los Angeles; Allison B. Sekuler, Department of Psychology, McMaster University, Hamilton, Ontario, Canada.

Sharon E. Guttman is now at the Department of Psychology, Vanderbilt University.

This research was supported by Natural Sciences and Engineering Research Council of Canada (NSERC) Student Research Awards and an NSERC Postgraduate Scholarship to Sharon E. Guttman, NSERC Research Grant OGP0105494 and a Canada Research Chair grant to Allison B. Sekuler, and National Institutes of Health Research Grant EY13518-01 to Philip J. Kellman. We thank Patrick Bennett, Paul Jaye, Robert Sekuler, Steve Yantis, and other anonymous reviewers for their helpful suggestions and comments on earlier versions of this article.

Correspondence concerning this article should be addressed to Allison B. Sekuler, Department of Psychology, McMaster University, Hamilton, Ontario L8S 4K1, Canada. E-mail: sekuler@mcmaster.ca

occlusion. Do more highly occluded objects require processing by different mechanisms than objects occluded by lesser amounts, or do they engage the same basic mechanisms for longer periods of time?

First, how general is the finding that time to completion increases with the size of the occluded region? To demonstrate visual completion, a partly occluded object must act as functionally equivalent to a complete object and functionally distinct from an incomplete object in some processing task. According to the temporal variation hypothesis, the time needed to achieve this functional completion should increase with the size of the occluded region.

Using a visual search paradigm, Rauschenberger and Yantis (2001) presented data that approach this theoretical ideal. Following previous researchers (Davis & Driver, 1998; He & Nakayama, 1992; Rensink & Enns, 1998), Rauschenberger and Yantis assumed that if the visual system represents only physically specified regions (i.e., a "mosaic" representation), then a partly occluded circle will "pop out" of a display containing complete circles, just as an incomplete circle would pop out of a group of circles. However, if the occluded circle is completed, then a slow, serial search will be required to detect it in a field of complete distractors, just as one particular circle would be relatively difficult to find among other circles. Rauschenberger and Yantis found that circles occluded by a small amount (9.0% of their area, 15.3% of their contour) were detected slowly when surrounded by complete circles, even if masked after only 100 ms of processing. Circles occluded by 25.0% (area or contour) were detected quickly in displays containing complete circles if the shapes were masked after 100 ms of processing; however, with longer exposure before masking (250 ms), the results were consistent with a slow, serial search. Circles occluded by a large amount (37.0% of their area, 30.6% of their contour) could be identified rapidly and efficiently when surrounded by complete circles, even at the longest presentation time (250 ms).

From these results, Rauschenberger and Yantis (2001) argued that early in processing, the representation of a partly occluded object differs from that of its complete counterpart, thus supporting an efficient parallel search; as processing proceeds, the representations of occluded and complete shapes become similar, thus necessitating a slow, serial search. More important, their results also suggest that the time required for this representational similarity increases with the amount of occlusion. However, the most highly occluded shapes never acted as functionally equivalent to the complete shapes. Thus, although we may predict that their completion would occur with additional processing time, another possibility arises: The visual system may be incapable of completing objects occluded by more than a certain amount. According to the *spatial limitation hypothesis*, the visual system represents highly occluded objects as incomplete, regardless of processing time.

A similar explanation may apply to an earlier study that manipulated amount of occlusion. Shore and Enns (1997) showed observers scenes containing complete shapes (see Figure 1A), partly occluded shapes (see Figure 1B), and mosaic shapes (see Figure 1C). For each image, observers made a speeded judgment concerning whether the black shape was a variant of a circle or a square. In general, observers classified complete shapes more rapidly than mosaic shapes; the researchers attributed this finding to the extra semantic processing necessary to infer the completion

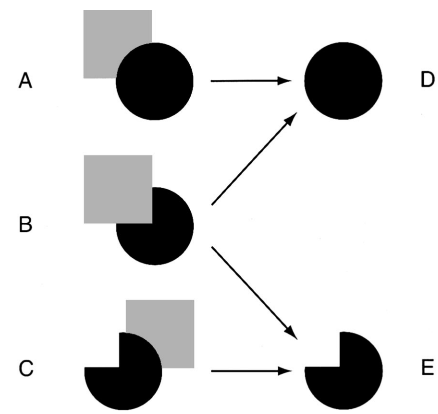

Figure 1. Partly occluded objects provide ambiguous sensory information to the visual system. A scene containing a partly occluded object (B) can be interpreted as two complete figures overlapping in depth (D) or as a mosaic composed of two fully specified shapes existing in the same depth plane (E). By contrast, both complete figures (A) and mosaic figures (C) result in unambiguous perceptual representations (D and E, respectively).

of mosaic shapes. Reaction times (RTs) for the occluded shapes depended on the size of the occluded region: With increasing amounts of occlusion, RTs transitioned gradually from the level produced by complete shapes to the level produced by mosaic shapes (Shore & Enns, 1997, Experiment 2).[1] Shore and Enns concluded that time to completion increases with amount of occlusion, thus lengthening the time needed to process more highly occluded shapes. However, as in Rauschenberger and Yantis (2001), one cannot conclude that completion ever occurred for the most highly occluded objects, because highly occluded objects never acted as functionally equivalent to the complete shapes. The long RTs produced by highly occluded objects may reflect extended semantic processing on a mosaic or partially interpolated representation, rather than increased time to completion.

To summarize, both of these studies (Rauschenberger & Yantis, 2001; Shore & Enns, 1997) provide suggestive evidence for the temporal variation hypothesis, particularly with regard to objects occluded by small or moderate amounts. This hypothesis has intuitive appeal: With longer processing times, the visual system can interpolate a greater amount of occluded information. The hypothesis also fits well with other data suggesting that time to completion depends on contextual factors (e.g., Bruno et al., 1997;

[1] The precise pattern of results across experiments varied somewhat, perhaps due to the introduction of additional manipulations, such as attention and motion. In the most basic experiment, shapes occluded by very small amounts (3.0%–5.0% of their area) produced uninformative results, due to minimal differences in the RTs for the complete and mosaic counterparts. Shapes occluded by 15.0% of their area (19.5% of the circle's contour and 22.9% of the square's contour) produced RTs that resembled those for the complete shapes but differed significantly from those for the corresponding mosaic shapes. Shapes with intermediate amounts of occlusion (25.0%–45.0% of the area, equal to 25.0%–34.0% of the circle's contour and 28.2%–35.0% of the square's contour) yielded intermediate RTs that differed significantly from those produced by both the complete and mosaic shapes. With large amounts of occlusion (50.0% or more of the surface area, equal to 36.1% of the contour for both shapes), RTs were virtually identical to those for the mosaic shapes.

Murray et al., 2001). Additionally, previous studies suggest that the amount of time necessary for contour closure of 2-D line drawings and interpolation of illusory figures increases as the size of the interruption in a contour increases (Elder & Zucker, 1993; Gegenfurtner, Brown, & Rieger, 1997). However, even assuming that a common mechanism underlies the completion of these various stimuli, none of these findings apply directly to *highly* occluded objects.

Indeed, theoretical considerations lend credence to the idea that objects occluded by a sizable amount may exceed the visual system's completion abilities. First, the visual system obviously requires some minimum of physically specified sensory input to guide completion. Second, Kellman and Shipley's (1991, 1992) theory of visual interpolation, some aspects of which have garnered considerable empirical support (Field, Hayes, & Hess, 1993; Kellman, Yin, & Shipley, 1998; Shipley & Kellman, 1990, 1992a, 1992b), predicts that large amounts of contour occlusion, in certain spatial arrangements, will prohibit the representation of partly occluded objects as complete. According to this theory, object completion requires that the contours leading into a discontinuity (i.e., disappearing behind an occluder) be *relatable*. Two partly occluded contours are relatable if their tangents at the points of discontinuity, when extended as straight lines, meet behind the occluder at an angle of no smaller than 90°. In other words, the theory predicts that interpolated contours bend monotonically, through a maximum of 90°. Thus, the completion of circles may disintegrate if a segment including more than 25.0% of the total contour is occluded, because the two edges leading into the discontinuities would no longer be relatable. (Of note, this is the highest level of occlusion for which Rauschenberger & Yantis, 2001, demonstrated the completion of circles.) Similarly, the relatability of squares breaks down as soon as one entire edge is occluded, so completion of very highly occluded squares also would not be expected.

An additional theoretical consideration with regard to spatial limitation involves the notion of support ratio—the ratio of physically specified length to total edge length. Several studies indicate that the perceived connectedness of two contour segments separated by an occluder, as well as illusory contour strength, increases with support ratio (e.g., Shipley & Kellman, 1992b). Moreover, with support ratio held constant, interpolated contour strength remains approximately constant across a wide range of stimulus sizes (and thus absolute gap sizes; Banton & Levi, 1992; Ringach & Shapley, 1996; Shipley & Kellman, 1992b). Because their visible contours are continuous, support ratio for circles occluded in a single region complements proportion of occlusion (e.g., a circle with .25 of its contour occluded has a support ratio of .75). A quantitative assessment of support ratio for corner-occluded squares is more difficult, as we might debate whether "total edge length" should include all edges of the square or just the partly occluded edges. Nonetheless, support ratio clearly decreases with increasing proportions of occlusion. Thus, the strength of contour interpolation should decrease with increasing occlusion, because of a lower support ratio. However, the support ratio (and corresponding proportion of occlusion) at which interpolation strength falls to zero has not been determined and may well vary with stimulus factors such as the curvature and spatial arrangement of the visible edges.

Due to the importance of contour-based notions such as support ratio and relatability for determining the strength of interpolation, all amounts of occlusion considered herein are given in terms of *percentage of occluded contour*. Accordingly, on the basis of both theoretical considerations (e.g., Kellman & Shipley, 1991) and empirical findings (e.g., Rauschenberger & Yantis, 2001), "highly occluded objects" will be provisionally defined as objects with more than 25.0% contour occlusion. However, we reiterate that the exact point at which interpolation processes should break down remains uncertain and likely depends on stimulus shape. At high levels of occlusion, completion may be constrained solely by spatial factors such as relatability and support ratio, as the spatial limitation hypothesis suggests, or by some combination of spatial factors and processing time.

Regardless of the range over which the temporal variation hypothesis is valid, we must ask *why* time to completion increases with the size of the occluded region. Both contour and surface interpolation mechanisms play a role in the completion of partly occluded objects, and both types of processes potentially could contribute to variations in completion time. For surface interpolation, several researchers have proposed a "surface-spreading" mechanism that involves the gradual, incremental completion of surface properties within interpolated boundaries (e.g., Grossberg & Mingolla, 1985; Kellman & Shipley, 1991; Yin, Kellman, & Shipley, 1997, 2000). The time required for such a process should increase with the size of the occluded region. However, although surface interpolation mechanisms can specify the surface properties of occluded regions and establish connections between fragments belonging to the same object, they cannot define the shape of an object's boundaries (Kellman, Guttman, & Wickens, 2001). In other words, surface processes alone cannot produce complete shape representations of partly occluded objects.

With regard to contour interpolation, some accounts suggest that completion occurs in an interactive network of orientation-sensitive units (e.g., Field et al., 1993; see also Kellman et al., 2001). According to this approach, physically specified edges activate some oriented units, causing a propagating "wave of activation" in collinear (or cocircular) units that do not receive direct stimulus input. Interpolation occurs between two physically specified edges whenever the units they activate intersect. Such accounts, complementary to the idea of surface spreading, essentially envision interpolation as an incremental filling-in process, based on the successive activation of adjacent neural units. The prediction that time to completion should rise with the distance between visible edges follows naturally from this theoretical approach.

Alternative explanations of edge interpolation, based on nonlinear inputs to higher-order operators (e.g., Heitger, von der Heydt, Peterhans, Rosenthaler, & Kübler, 1998), also could account for increasing time to completion with amount of occlusion, although the prediction arises less naturally. In these accounts, higher-order operators collect input from units that respond to real edge segments on either side of a gap; responses in both input units simultaneously lead to interpolation across the gap. As gap size increases, less of the physically specified edges may fall within the receptive fields of the input units, thus lowering their activation level. This decrease could, theoretically, cause activity in the higher-order operator to reach the threshold for interpolation more gradually. Thus, time to completion may increase as a function of the size of the occluded region.

These different accounts of edge interpolation converge on an important point: Time to completion rises with amount of occlusion because of variations in the time needed to execute a single, low-level mechanism. However, another possibility must be entertained: Variations in completion time may reflect a spatial limit for the operation of low-level edge interpolation mechanisms. By this explanation, low-level contour completion mechanisms, which likely proceed rapidly, operate only on objects occluded by small or moderate amounts. Thus, the visual system must engage alternative, time-consuming mechanisms to achieve the phenomenological completion of more highly occluded objects. Accordingly, completion times would rise with the spatial extent of occlusion.

This notion—that the visual system relies on qualitatively different processes for the completion of objects occluded by different amounts—becomes especially plausible if we find that the temporal variation hypothesis extends to objects occluded by more than some theoretical spatial limit, such as the monotonicity constraint in relatability theory (Kellman & Shipley, 1991), which requires that occluded contours bend through no more than 90°. Indeed, low-level contour interpolation mechanisms might operate only on shapes with highly relatable edges. When visible edges approach or exceed the limit of relatability, visual completion might occur only when stimulus variables support alternative modes of processing. For the completion of occluded circles and squares, higher-level mechanisms based on symmetry (Boselie, 1994; Sekuler, 1994; Sekuler, Palmer, & Flynn, 1994; van Lier & Wagemans, 1999) or familiar shape (e.g., Kanizsa & Gerbino, 1982) represent two such alternative processing routes. Toward the limit of relatability, such processes may supplement weak contour interpolation; when relatability criteria are exceeded altogether, the visual system may rely purely on the recognition of partial information to activate a complete representation of the object in question (Kellman, 2000; Kellman et al., 2001). Thus, variations in time to completion may reflect the number and complexity of processes needed to achieve complete shape representations, rather than (or in addition to) differences in the amount of time needed to execute low-level interpolation mechanisms.

The first experiment of the current study focuses on the question of whether the visual system can form complete representations of highly occluded objects—those with more than 25.0% contour occlusion—if given enough time. To this end, we used a priming paradigm to control the point at which perceptual processing is interrupted and a pattern's representation is probed, thus allowing investigation of the time course of visual completion (Sekuler & Palmer, 1992). At different processing durations, we examined the early representations of objects occluded by moderate amounts (20.0% of their contour) and highly occluded objects (32.5% of their contour), both with and without relatable edges.

In two further experiments, we investigated *why* time to completion rises with the size of the occluded region. Here, a dot-localization paradigm probed the final contour representations of objects occluded by various amounts. Previous research suggests that low-level edge interpolation mechanisms lead to precisely localized contours, whereas alternative processing strategies, such as those based on the recognition of partial information, result in much "fuzzier" edge representations (Guttman & Kellman, 2002; Kellman, Shipley, & Kim, 1996; Kellman, Temesvary, Palmer, & Shipley, 2000). Thus, if differences in time to completion can be attributed to temporal variations within the same basic completion mechanisms, then interpolated contours should be represented with similar levels of precision regardless of the size of the occluded region, and any change in precision should be a gradual function of amount of occlusion. By contrast, if time to completion rises because additional processing mechanisms must be engaged once the amount of occlusion has exceeded some spatial limit, then there should be a categorical difference in contour precision between the objects on either side of this limit. Thus, the results of these experiments should yield new insights into the basis of temporal variations in visual completion.

Experiment 1

The first experiment used the primed-matching paradigm to investigate the time course over which objects occluded by various amounts become completed. In the primed-matching paradigm, observers view a priming stimulus and then make a "same" or "different" decision about a pair of test shapes. Previous research within this paradigm has shown that RTs to correctly identify "same" pairs depend on the representational similarity of the test shapes to the prime (Beller, 1971; Rosch, 1975a, 1975b). So, for example, if people see a complete circle as a prime, they are faster at saying "same" to a pair of complete circles than to a pair of mosaic circles (see Figure 2A). Conversely, if the prime is a mosaic circle, observers are faster at saying "same" to a pair of mosaic circles than to a pair of complete circles (see Figure 2B). The critical question concerns whether an occluded prime produces a pattern of priming more like its complete or mosaic interpretation (see Figure 2C). An occluded prime is considered complete when it first produces priming effects that differ significantly from those of a mosaic prime but not from those of a complete prime. By manipulating duration of exposure to the prime, one can map the *microgenesis,* or developmental time course, of visual completion (Sekuler & Palmer, 1992).

The purpose of the first experiment was to determine whether highly occluded objects can be completed, given enough time, or whether some spatial limit precludes their completion altogether. To this end, we examined completion effects of circles and squares with 20.0% and 32.5% contour occlusion, at stimulus onset asynchronies (SOAs) ranging from 75 to 750 ms. If the visual system cannot complete objects occluded by more than 25.0%, then the primes occluded by 20.0% should produce patterns of priming equivalent to their complete counterparts at some SOAs—those allowing sufficient processing to achieve completion—whereas the primes occluded by 32.5% should produce patterns of priming

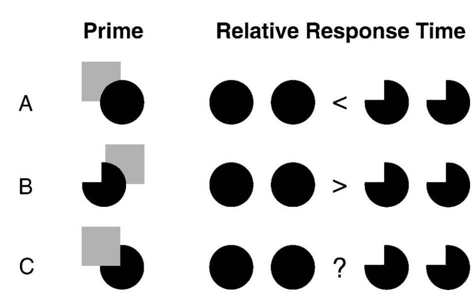

Figure 2. Schematic representation of relative response times to various test pairs. After seeing a complete prime (A), people are faster at responding "same" to a pair of complete shapes than to a pair of mosaic shapes. After seeing a mosaic prime (B), people are faster at responding "same" to a pair of mosaic shapes than to a pair of complete shapes. The pattern of responses to the occluded prime (C) should reveal how the visual system represents partly occluded objects.

equivalent to their mosaic counterparts (or, if partial interpolation occurs, some intermediate pattern of priming), regardless of SOA. Alternatively, spatial limits based on contour relatability (Kellman & Shipley, 1991, 1992), rather than the size of the occluded region per se, may constrain the completion of partly occluded shapes. In this case, the squares with 32.5% contour occlusion should eventually produce "complete" patterns of priming (although at longer SOAs than the shapes occluded by 20.0%), whereas the circles with 32.5% contour occlusion should not. Finally, the temporal variation hypothesis may be valid across the entire range of tested occlusion levels. If so, then all of the occluded shapes will eventually produce equivalent patterns of priming to their complete counterparts; however, the shapes occluded by 32.5% should take longer to achieve this equivalence than the shapes occluded by 20.0%.

Method

Observers. One hundred thirteen observers (80 women and 33 men) participated in the experiment. All observers were between the ages of 18 and 28 (mean age = 21.0 years). Criteria for participation included normal or corrected vision and experimental naivete. Observers received course credit in an introductory psychology class at the University of Toronto, Toronto, Ontario, Canada, or were paid $7.50 per hour for their participation.

Design. The experiment consisted of the factorial combinations of six factors in a within-subject design: *prime type* (complete, occluded, mosaic, or no-prime); *correct response* (same or different); *test pair type* (complete or mosaic); *shape of relevant figure* (circle or square); *type of irrelevant figure* (complete or mosaic); and *orientation of prime* (left or right). Every combination of these factors was tested four times in block-randomized order. Two additional between-subjects factors were tested: *amount of contour occlusion* (20.0% and 32.5%) and *SOA* (75 ms, 135 ms, 255 ms, and 750 ms; 450 ms for the 32.5% condition only). Twelve randomly assigned observers participated in each of the nine conditions; additional observers replaced discarded data (see the *Analysis* section below), so that data from 12 observers per condition entered the final analysis.

Apparatus. A Macintosh IIx with a 50-MHz accelerator generated the experimental trials by using PsyScope 1.0.1 (Cohen, MacWhinney, Flatt, & Provost, 1993). Observers viewed stimuli on a 13-in. (33.02-cm) Apple-Color High-Resolution RGB Monitor (72 pixels/in.; 66.7 Hz screen refresh, noninterlaced). Observers responded by pressing one of two buttons on a Carnegie Mellon University button box connected to the computer, which recorded RTs to the nearest millisecond. Observers sat 100 cm from the screen with their heads stabilized by a chin and forehead rest. The testing room was illuminated only by the computer screen.

Stimuli. Figure 3 depicts examples of each type of priming display. Priming stimuli consisted of combinations of modified circles and squares in one of three configurations: complete, occluded, or mosaic (see Figures 3A, 3B, and 3C, respectively). The lower, black figure of each combination was the prime, and the upper, gray figure was irrelevant. The irrelevant figure was a complete or notched square when the prime was a complete or partial circle (top row in each cell of Figure 3), and it was a complete or notched circle when the prime was a complete or partial square (bottom row in each cell of Figure 3). The prime always appeared in the center of the screen; the irrelevant figure appeared above and to the right of the prime on half of the trials and above and to the left of the prime on the other half. A fourth priming condition, no-prime, consisted of two black dots centered where each of the two shapes in a priming display otherwise appeared (see Figure 3D).

The amount by which the irrelevant figure covered the occluded primes varied between observers. Complete primes always overlapped the accompanying irrelevant figure by the same amount that the irrelevant figure covered the occluded primes. Furthermore, the gap size in the mosaic

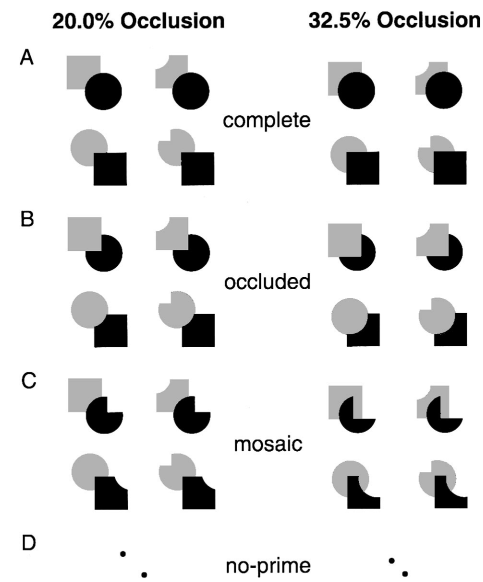

Figure 3. Representative priming stimuli with 20.0% occlusion (left column) and 32.5% occlusion (right column): complete primes (A), occluded primes (B), mosaic primes (C), and no-primes (D). The lower figure in each priming combination comprised the prime. Left–right reflections of each depicted stimulus also were used.

primes always matched the amount of occlusion in the corresponding occluded primes. Priming stimuli corresponding to 20.0% contour occlusion appear in the left half of Figure 3; priming stimuli corresponding to 32.5% contour occlusion appear in the right half of Figure 3.

As in earlier experiments (Sekuler & Palmer, 1992), the test displays contained three separate figures: two test shapes (the test pair) and one irrelevant figure.[2] The experiment used four basic types of test pairs: same–complete, same–mosaic, different–complete, and different–mosaic (see Figure 4). Same–complete test pairs consisted of two identical circles or two identical squares (see Figure 4A). Different–complete test pairs contained one circle and one square (see Figure 4B). Same–mosaic test pairs consisted of two identical notched circles or two identical notched squares (see Figure 4C). Different–mosaic test pairs contained one notched circle and one notched square (see Figure 4D). Within mosaic test pairs, the notches always appeared on the same side of the two shapes. Furthermore, mosaic test shapes that followed occluded or mosaic primes were always notched by the same amount and on the same side as in the priming stimulus; mosaic test shapes following no-primes and complete primes contained notches of the same size as in the other conditions, but the notch appeared on the left and right equally often.

For all test pairs, one test shape was positioned to the left of the screen's center and the other shape was positioned to the right of the screen's center. For "different" test pairs, the relative position of the two shapes was randomly left or right. This irrelevant figure in the test display essentially matched the irrelevant figure in the preceding priming stimulus; irrelevant figures previously occluded by complete or mosaic primes were completed in the test display. The irrelevant figure appeared immediately above its

[2] Previous research suggests that without the irrelevant figure in the test stimulus, observers perceive apparent motion (with an apparent shape change) from the irrelevant figure in the priming stimulus to one of the test shapes (Sekuler & Palmer, 1992). Little or no basic shape priming occurs under these conditions. When an irrelevant figure appears in the test stimulus, apparent motion perceptually links the two irrelevant figures to one another and basic shape priming is restored.

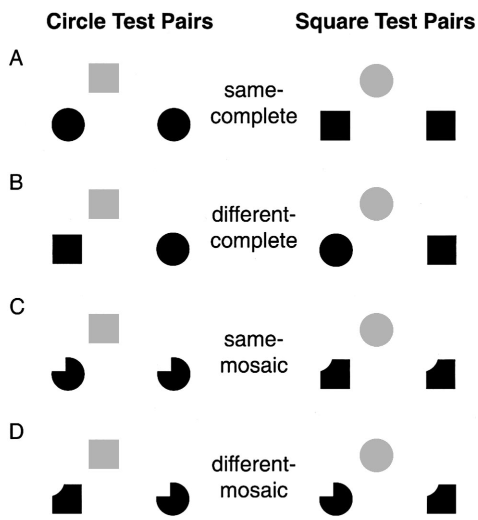

Figure 4. Examples of the four classes of test pairs that might follow the primes with 20.0% occlusion depicted in Figure 3: same–complete test pair (A), different–complete test pair (B), same–mosaic test pair (C), and different–mosaic test pair (D). The lower, black shapes composed the test pair; the upper, gray shape was irrelevant. Note that the orientation of the mosaics and the position of the irrelevant figure depended on the type and orientation of the preceding prime stimulus, as described in the text.

previous position in the prime, with its bottom edge at the same level as the top edge had been before.

Primes and test shapes were black (0.9 cd/m^2), and irrelevant figures were middle gray (36.5 cd/m^2). All stimuli appeared on a white background screen (105 cd/m^2). Circles and squares measured 0.82° and 0.73° in diameter, respectively, equating area. The maximum extent of the largest priming display was 1.24° both horizontally and vertically. The maximum extent of the largest test configuration was 3.44° × 2.06°. Test shapes were separated horizontally by 2.62°, measured from center to center; the vertical distance from the test shapes to the irrelevant figure depended on the amount of occlusion in the prime.

Procedure. A trial consisted of three frames: fixation, priming stimulus, and test stimulus. Figure 5 schematizes a typical trial. First, a fixation point appeared in the center of the screen for 255 ms (see Figure 5A), then the screen went blank for another 240 ms. In the second display, a combination of figures (the priming stimulus) or two dots (for the no-prime condition) appeared for either 45, 105, 225, 420, or 720 ms (see Figure 5B), followed by a 30-ms interstimulus interval (ISI; yielding SOAs of 75, 135, 255, 450, and 750 ms). Finally, the test display appeared, remaining on the screen until the observer indicated whether the two black shapes in the test pair were the same or different as one another (see Figure 5C).

Observers were instructed to respond as quickly as possible by pressing one of two response buttons. Because our analyses deal only with “same” responses, all observers pressed the “same” button with their dominant hand and the “different” button with their nondominant hand. The computer recorded responses and RTs to the nearest millisecond, and presented auditory feedback for incorrect responses. The intertrial interval was approximately 2,500 ms.

To encourage attention to the prime, the experimenter told observers that the lower part of the figure in the second frame would help them know what to expect in the third frame. If the prime had “mostly curved edges,” observers should expect figures with “mostly curved edges” in the subsequent test pair. If the prime had “mostly straight edges,” observers should expect figures with “mostly straight edges” in the subsequent test pair. In keeping with this statement, the figures presented in the test pair depended on the shape of the preceding prime: Same test pairs that followed circular primes were complete or notched circles, and same test pairs that followed square-based primes were complete or notched squares. However, either complete or mosaic test pairs could follow any of the prime types. In the no-prime control condition, observers received no advance information about the shapes in the test pair; the third frame could contain any pair of test figures allowed in the other prime conditions.

Each test block contained five practice trials, followed by 64 same and 64 different trials presented in random order. Observers completed four blocks of trials for a total of 512 experimental trials. In addition, 20 practice trials preceded the test blocks. Observers controlled the amount of time between blocks, and each session lasted approximately 1 hr.

Analysis. For inclusion in the final analysis, an individual’s data were required to meet two criteria: fewer than 10.0% overall errors and a median RT within 3 *SD*s of the group mean of medians. The data from 1 observer failed to meet the first criterion, and the data from 3 other observers failed to meet the second criterion. The data from 1 additional observer were discarded because she reported difficulty distinguishing between the prime and the irrelevant figure. Thus, these 5 of the original 108 observers were replaced.

A meaningful analysis of error rates could not be performed as most observers made very few errors (mean error rate = 2.0%). However, errors did not appear to be consistent with a speed–accuracy trade-off.

Priming acted as the dependent variable for all reported analyses. The priming measure, calculated for each individual prime type, indicates how much the prime in question speeded up “same” responses to complete test pairs relative to mosaic test pairs. Computationally, the amount of priming afforded by a given prime is defined as the difference in median times to respond “same” to a mosaic pair versus a complete pair after seeing the prime, minus the baseline response difference to these test pairs in the no-prime condition (see Equation 1):

$$\text{Priming} = [\text{RT}(\text{mosaic}|\text{prime}) - \text{RT}(\text{complete}|\text{prime})] - [\text{RT}(\text{mosaic}|\text{no-prime}) - \text{RT}(\text{complete}|\text{no-prime})]. \quad (1)$$

A complete prime should produce priming values of greater than zero, caused by shorter RTs to complete test pairs than to mosaic test pairs, relative to any RT difference between the no-prime conditions. Similarly, a mosaic prime should produce priming values of less than zero, caused by shorter RTs to mosaic test pairs than to complete test pairs, relative to any RT difference between the no-prime conditions. The priming afforded by an occluded prime depends on its representation. If the occluded prime is represented as a mosaic, then it should produce a priming value similar to that of its mosaic counterpart. However, if the occluded prime is represented as complete within the visual system, then it should produce a priming value similar to that of its complete counterpart.

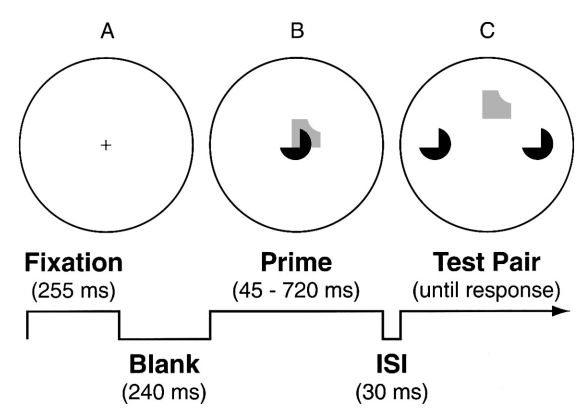

Figure 5. Sequence of events for each trial in Experiment 1: fixation point (A), priming stimulus (B), and test stimulus (C). ISI = interstimulus interval.

Table 1
Mean Reaction Times Across Different Amounts of Contour Occlusion and SOAs (Experiment 1)

	Complete test pair				Mosaic test pair			
Condition	Com	Occ	Mos	None	Com	Occ	Mos	None
Circle primes								
20.0%								
75 ms	470.0	477.2	487.2	455.6	551.0	538.7	507.0	515.4
135 ms	458.2	469.3	510.3	488.0	551.5	544.5	511.3	539.1
255 ms	398.4	407.7	461.1	438.0	493.0	489.3	432.8	484.7
750 ms	399.4	392.3	455.2	431.5	509.0	484.2	442.5	495.4
32.5%								
75 ms	417.5	424.7	456.6	426.7	548.0	507.7	467.0	506.6
135 ms	455.0	471.0	504.3	461.0	583.0	557.4	503.0	550.2
255 ms	428.0	442.0	518.3	488.3	557.8	514.5	464.7	548.1
450 ms	388.1	398.0	452.3	434.2	509.3	512.0	442.5	496.3
750 ms	423.7	442.9	475.4	481.3	524.4	524.2	471.8	516.6
Square primes								
20.0%								
75 ms	467.7	476.3	497.8	465.6	535.1	541.7	511.2	524.9
135 ms	492.5	476.9	533.8	513.3	602.2	558.7	528.8	578.8
255 ms	410.6	432.9	478.3	485.2	503.0	504.9	455.9	548.3
750 ms	398.5	397.2	452.0	468.4	530.2	506.7	458.5	526.8
32.5%								
75 ms	419.4	445.3	490.6	435.0	559.1	527.0	492.4	546.0
135 ms	465.0	483.5	532.8	506.7	599.8	572.2	533.4	578.9
255 ms	440.8	469.1	531.2	500.4	576.4	539.7	479.0	555.1
450 ms	396.5	411.0	475.5	476.0	530.0	507.8	463.4	507.8
750 ms	423.3	442.2	517.1	507.7	551.0	539.3	491.3	550.8

Note. All numerical values are the means of the individual observers' median reaction times, in milliseconds, for the condition in question. "Condition" refers to the stimulus onset asynchrony (SOA) and amount of contour overlap associated with each prime. Com = complete prime; Occ = occluded prime; Mos = mosaic prime; None = no-prime.

An overall analysis of variance (ANOVA) of priming was performed with SOA (75 ms, 135 ms, 255 ms, and 750 ms) and amount of contour occlusion (20.0%, 32.5%) as between-subjects variables and prime type (complete, occluded, mosaic) and shape of prime (circle, square) as within-subject variables.[3] Planned comparisons then were performed to determine the conditions in which the occluded primes were represented as "complete" in the perceptual system. For an occluded prime to be deemed perceptually complete, the priming effects for occluded and complete primes could not differ significantly from one another, and both of these priming effects had to be statistically different from the priming effects for a mosaic prime. All three comparisons relied on *t* tests at the .05 level of significance.[4]

Results and Discussion

Mean RTs for each condition are presented in Table 1. All other reported data and statistics rely on the derived priming measure, described above.

Figure 6 depicts the priming effects as a function of SOA. Circles with 20.0% occlusion appear in Figure 6A, squares with 20.0% occlusion appear in Figure 6B, circles with 32.5% occlusion appear in Figure 6C, and squares with 32.5% occlusion appear in Figure 6D. As discussed previously, priming values of greater than zero indicate a "complete" representation (faster responses to complete test pairs than to mosaic test pairs), whereas priming values of less than zero indicate a "mosaic" representation (faster responses to mosaic test pairs than to complete test pairs).

An examination of this figure reveals several important effects. First, highly reliable basic shape priming occurred in all conditions. That is, complete primes produced priming values greater than zero and mosaic primes produced priming values less than zero. Basic shape priming was confirmed by the overall ANOVA, which indicated a main effect of prime type, $F(2, 176) = 239.9$,

[3] The 450-ms SOA—collected only for shapes occluded by 32.5%—was excluded from the overall ANOVA because of asymmetry in the conditions. Data from the 450-ms priming condition were analyzed by using the same pairwise comparisons and definition of completeness as in the description that follows.

[4] The alpha level was not adjusted for two reasons. First, the theoretical increase in Type I error is of minimal concern for planned comparisons, provided the comparisons are meaningful and not haphazard (Keppel & Saufley, 1980). Second, and more important, the determination of whether an occluded prime is represented as perceptually complete requires the demonstration that its priming effects are statistically different from those of a mosaic prime but *not* statistically different from those of a complete prime. Consequently, reducing the alpha level to account for the multiple comparisons could produce artifactual results (e.g., finding completion where none truly exists).

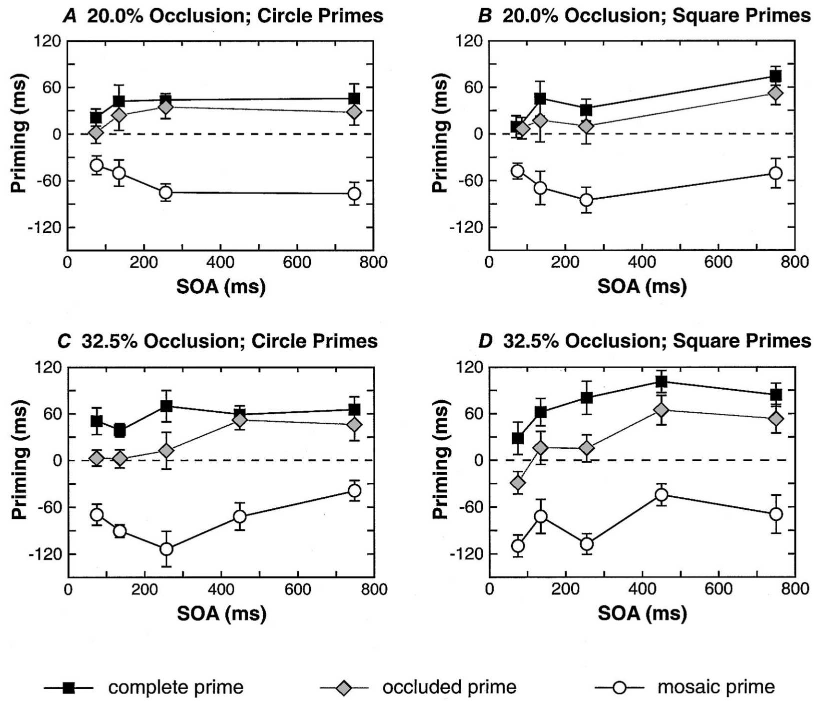

Figure 6. Results for Experiment 1: priming effects for different prime types as a function of stimulus onset asynchrony (SOA). Each graph depicts data for a different combination of amount of occlusion and prime shape. Values of greater than 0 indicate an advantage in responding to complete test pairs; values of less than 0 indicate an advantage in responding to mosaic test pairs. Error bars represent plus or minus one standard error of the mean across observers.

$p < .0001$; additionally, planned pairwise comparisons indicated significant differences in priming levels between complete primes and the corresponding mosaic primes for all conditions. These findings validate the priming manipulation.

Second, the graphs in Figure 6 suggest that circles and squares produced highly similar patterns of priming. The main effect of shape did not approach significance ($F < 1$, *ns*), nor was shape involved in any significant interactions. Given that the squares with 32.5% contour occlusion contained relatable edges but the circles with 32.5% contour occlusion did not, this finding poses a possible challenge to the relatability hypothesis (Kellman & Shipley, 1991, 1992).

Third, and perhaps most important, occluded primes produced different effects depending on amount of occlusion and prime duration. The overall ANOVA supports this conjecture; despite fairly consistent basic shape priming, prime type interacted significantly with both amount of occlusion, $F(2, 176) = 7.03$, $p < .0001$, and SOA, $F(6, 176) = 2.89$, $p < .05$. The main effect of SOA also was significant, $F(3, 88) = 3.92$, $p < .05$. No other main effects or interactions reached significance. What do these variations in priming indicate about visual completion processes?

One important finding concerns the issue of spatial limitation: At 420 ms of priming and beyond, both circles and squares with 32.5% contour occlusion produced similar priming effects to their complete counterparts. This "complete" interpretation of the highly occluded primes is confirmed by the planned comparisons. At SOAs of 450 ms and 750 ms, occluded circles and squares both produced priming effects that were statistically indistinguishable from the corresponding complete primes, but differed significantly from the corresponding mosaic primes (all *t* tests performed with $\alpha = .05$). These data represent the first conclusive demonstration that the visual system can complete highly occluded objects (i.e., objects with more than 25.0% contour occlusion), given enough processing time. In terms of area, the circles in the 32.5% contour occlusion condition were occluded by 41.5% and the squares were occluded by 35.6%. Therefore, this finding of completion for highly occluded objects extends earlier results, which were inconclusive regarding whether completion is possible if more than 25.0% of an object's area is occluded (Rauschenberger & Yantis, 2001; Shore & Enns, 1997). Moreover, the fact that the circles with 32.5% contour occlusion exceed the limits of relatability but nevertheless achieved a complete representation indicates that, with sufficient time, the visual system can complete at least some nonrelatable objects.

Overall, the observed patterns of priming are consistent with the temporal variation hypothesis. At all tested SOAs, the circles and squares with 20.0% contour occlusion produced priming effects that were statistically indistinguishable from their complete counterparts but differed significantly from their mosaic counterparts. By contrast, the shapes with 32.5% contour occlusion did not achieve completion until an SOA of 450 ms; at the shorter SOAs (75 ms, 135 ms, and 255 ms), the occluded shapes produced priming effects that differed significantly from both the complete shapes and the mosaic shapes. Therefore, with the larger amount of occlusion, observers required longer priming durations to produce statistically equivalent priming effects for complete and occluded primes.[5]

To quantify more precisely the extent of completion over time, we defined a completion index, *c*, calculated from the mean complete, occluded, and mosaic priming values:

$$c = \frac{\text{occluded} - \text{mosaic}}{\text{complete} - \text{mosaic}}. \quad (2)$$

On this index, a value of 1 indicates that the visual system treated the occluded object as identical to its complete counterpart; a value of 0 indicates that the visual system treated the occluded object as identical to its mosaic counterpart. Following Murray et al. (2001), we take values of .8 or greater to show functional equivalence of occluded and complete objects, and values of .2 or less to show functional equivalence of occluded and mosaic objects. Figure 7 plots the completion indices as a function of SOA for objects with 20.0% and 32.5% occlusion, collapsed across prime shape. For objects with 20.0% occlusion, *c* is near .8 at even the shortest SOA tested (75 ms) and remains essentially constant for longer durations.[6] By contrast, for objects with 32.5% occlusion, *c* first exceeds .8 at an SOA of 450 ms.

We should note that although percentage of contour occlusion, which is closely linked to support ratio, seems to be an appropriate spatial metric for determining strength of contour interpolation and thus any possible spatial limits, time to completion might depend more on absolute gap size in retinal coordinates. Thus, the estimated completion times (as early as 75 ms for objects with 20.0% contour occlusion; 450 ms for objects with 32.5% contour occlusion) may not apply directly to similar objects of different retinal size. Nonetheless, the results support our overall conclusion that time to completion varies with amount of occlusion.

In sum, our results converge with previous studies (Rauschenberger & Yantis, 2001; Shore & Enns, 1997) in suggesting that the visual system quickly completes objects with relatively small amounts of occlusion. Additionally, these data extend previous research by showing conclusively that the visual system also can complete more highly occluded objects (up to at least 32.5% of the contour), even those with contours exceeding the limits of relatability. However, level of occlusion has a substantial effect on time to completion; as much as several hundred milliseconds more processing time may be required to complete highly occluded objects.

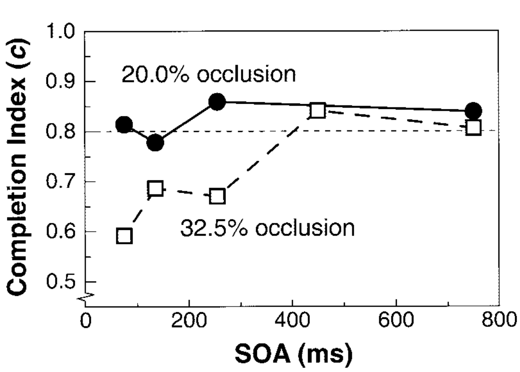

Figure 7. Completion index values (*c*) as a function of stimulus onset asynchrony (SOA) for objects with 20.0% occlusion and 32.5% occlusion. A value of 1 on the completion index indicates that the occluded object produced an identical priming value to its complete counterpart; a value of 0 indicates that the occluded object produced an identical priming value to its mosaic counterpart. The horizontal line shows the level above which we took the occluded prime to have an essentially "complete" representation.

Experiment 2

The results of Experiment 1 indicate that time to completion rises with increasing amounts of occlusion. The simplest explanation for this finding implicates processing variations within low-level interpolation mechanisms that gradually "fill-in" partly occluded contours and surfaces. However, given the finding that the visual system can complete highly occluded objects, including those with nonrelatable edges, if given enough processing time, an alternative explanation must be considered. Time to completion may rise with amount of occlusion because, beyond some spatial limit, low-level contour interpolation mechanisms cease to operate; surface interpolation mechanisms may continue to operate beyond this limit, but cannot produce a complete representation of object shape (Kellman et al., 2001). Thus, under these circumstances, complete shape representations of partly occluded objects may be achieved only through the operation of additional, higher-order mechanisms, such as those based on the recognition of partial information.

Experiments 2 and 3 were designed to distinguish between these explanations for the observed variations in time to completion. We used a dot-localization paradigm to probe the precision with which the visual system ultimately represents the contours of objects occluded by different amounts (Guttman & Kellman, 2002; Kellman et al., 1996, 2000). In this paradigm, a partly occluded object is presented with a small dot superimposed somewhere on the occluder. On each trial, observers judge whether the dot appears inside or outside of the occluded shape's perceived boundary. Two interleaved staircase procedures, converging on two different points of the underlying psychometric function, are used to estimate the location at which observers perceive the contour and the precision of contour perception. If contour completion mechanisms interpolate an edge in a relatively precise place, then relatively precise dot localization should result (Guttman & Kellman, 2002; Kellman et al., 1996, 2000). By contrast, if a display suggests a certain form due to higher-level recognition processes, then the resulting shape representation may not support precise dot localization.

In Experiment 2, we examined the final edge representations of shapes with 20.0% and 32.5% contour occlusion. To ensure suf-

[5] The comparison between squares occluded by 32.5% and their complete counterparts actually fell just short of significance at the 255-ms SOA, $t_{11} = 2.18$, $p = .052$. However, the graph in Figure 6D is not generally consistent with completion by 255 ms, although a few observers may have achieved this effect.

[6] Despite this suggestion of completion at 75 ms, the complete and occluded shapes actually produced near-zero priming values at this SOA, thus limiting our ability to interpret whether the objects occluded by 20.0% actually were completed at the shortest processing duration. We can be more confident that completion occurred at the 135-ms SOA, despite the completion index falling just short of the .8 criterion, as all priming values were significantly nonzero at this duration. Regardless, the completion of objects occluded by 20.0% unquestionably first occurred at shorter processing durations than the completion of objects occluded by 32.5%.

ficient processing time, the stimuli appeared for 480 ms prior to dot presentation, a duration exceeding all times to completion measured in Experiment 1. We limited our examination to partly occluded circles because (a) no difference in the processing of circles and squares was found in Experiment 1 and (b) the more highly occluded circles contain nonrelatable edges and thus can be used to test directly the idea that different processing mechanisms must be engaged above the spatial limit proposed by the relatability hypothesis (Kellman & Shipley, 1991, 1992). Additionally, we used stimuli of two sizes, chosen such that 32.5% of the smaller circle's contour was equal in length to 20.0% of the larger circle's contour. Thus, we were able to determine whether any observed differences in precision depended on the percentage of an object that was occluded or on the absolute length of occluded contour (and thus distance from physically specified edges).

Contour interpolation mechanisms should, in theory, generate an interpolated contour in a precise location and thus should support relatively precise dot-localization performance (Guttman & Kellman, 2002; Kellman et al., 1996, 2000). Therefore, if the same low-level edge interpolation mechanisms operate on circles occluded by 20.0% and 32.5%, then their interpolated contours should be represented with similar, high precision. Alternatively, some partly occluded objects—either because their edges are nonrelatable or because they have exceeded a spatial limit based on some other criterion—may be represented as complete because of additional processes based on symmetry or the recognition of partial information. Shape representations achieved through these means may not support precise dot-localization performance. Therefore, if circles occluded by 32.5% become completed through a different route than circles occluded by 20.0%, then significantly different levels of contour precision should result. Specifically, we would expect the contours of the highly occluded circles to be represented much less precisely than their moderately occluded counterparts.

Method

Observers. Thirteen University of California, Los Angeles (UCLA) undergraduates (2 women, 11 men) between the ages of 18 and 24 years (mean age = 20.1 years) and naive to the hypotheses participated in the experiment. All observers had normal or corrected-to-normal vision and received partial course credit for their participation.

Apparatus. The experimental trials were generated by using MacProbe 1.8 on a Macintosh PowerPC G4 processor (450 MHz). Observers viewed stimuli on a Viewsonic P225f 22-in.(55.88-cm) Color Monitor (set to a resolution of 1,280 × 1,024 pixels; 75 Hz screen refresh) and responded by pressing one of two keys on the keyboard. As before, observers sat 100 cm from the screen in a dark testing room, with their heads stabilized in a chin-and-forehead rest.

Stimuli. Each stimulus consisted of a black circle occluded in the upper left quadrant by a gray square (akin to the circular occluded primes in Figure 3). The amount of contour occlusion (20.0%, 32.5%) varied within observers, as did the overall size of the stimuli. The smaller stimuli matched those used in Experiment 1: The circles measured 0.82° in diameter and the squares measured 0.73° along each edge, producing a maximum overall configuration of 1.20° both horizontally and vertically. The larger stimuli were expanded by 62.5%, such that the large circle occluded by 20.0% had the same absolute amount of contour occlusion as the small circle occluded by 32.5%; these larger circles and squares measured 1.33° and 1.17° in diameter, respectively, for a maximum overall configuration of 1.95° × 1.95°. Stimulus position was jittered ±0.20° from trial to trial. Luminance levels measured 0.72 cd/m^2 for the black circles and 56.4 cd/m^2 for the gray occluders; all stimuli appeared on a white background (111 cd/m^2).

Procedure. A schematic illustration of the trial structure appears in Figure 8. Each trial began with the presentation of a stimulus for 600 ms (see Figure 8A). During the last 120 ms of stimulus presentation, a small red dot (2.0 min of arc × 2.0 min of arc) was superimposed on the square, near the occluded edge of the circle (see Figure 8B). Finally, a mask consisting of random ellipses of various gray levels appeared until response (see Figure 8C).

Observers reported whether the red dot appeared inside or outside the perceived boundary of the circle by pressing one of two response keys. Instructions emphasized the need for accuracy; no feedback was given. Observers initiated each trial by pressing the spacebar, producing a variable ISI.

For each stimulus, the position of the probe dot varied on the basis of two interleaved 3-up/1-down staircases. The *inside* (3-up/1-down) staircase converged on the point on the psychometric function at which the observer's probability of an "inside" response was .79; the *outside* (3-down/1-up) staircase converged on the point on the psychometric function at which the observer's probability of an "outside" response was .79 (see Derman, 1957). For the inside staircases, the probe dot initially appeared 11.4 min of arc inside of the circle's occluded contour (see Figure 9). The dot remained in this position until the observer made "inside" responses on three consecutive presentations of the staircase or a single "outside" response. Three "inside" responses caused the task to be made harder: The dot appeared less inside on the next trial (i.e., it was shifted up and to the left). One "outside" response caused the task to be made easier: The dot appeared more inside on the next trial (i.e., it was shifted down and to the right). For the outside staircases, the reverse was true: The probe dot initially appeared 11.4 min of arc outside of the occluded contour. Three consecutive "outside" responses caused the dot to be shifted toward the inside; a single "inside" response caused the dot to be shifted further outside.

The probe dot always appeared along an imaginary line joining the top-left and bottom-right corners of the occluding square (see Figure 9). Initially, changes in dot location occurred in 7.1 min of arc increments; this continued until the staircase in question underwent two reversals of direction in the dot's position changes. Subsequently, the dot shifted in 4.3 min of arc increments for four reversals. Seventeen reversals at 1.4 min of arc increments completed the staircase.

The full experiment consisted of eight interleaved staircases (2 amounts of occlusion × 2 stimulus sizes × 2 staircase directions), with trials from each staircase presented in random order. The experiment continued until all staircases converged. Most observers completed the experiment in approximately 30 min. A short break was given every 200 trials.

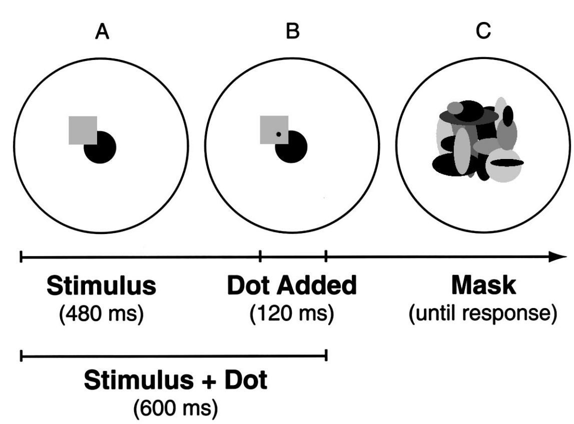

Figure 8. Sequence of events for each trial in Experiment 2: stimulus (A), stimulus with dot superimposed (B), and mask (C).

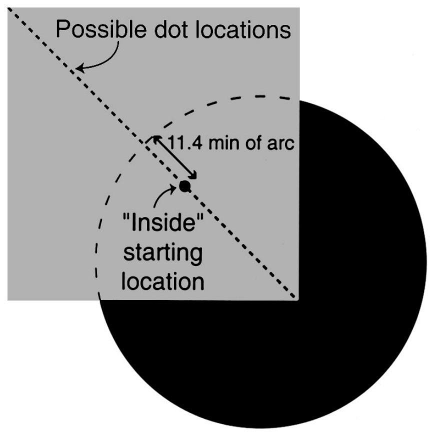

Figure 9. Schematic diagram of dot placement in Experiment 2. Initially, the dot appeared 11.4 min of arc inside or outside of the circle's occluded contour (starting position for an "inside" staircase is shown here). The dotted line indicates other valid dot locations that could appear during the staircase procedure.

Analysis. For each staircase, we averaged the dot locations giving rise to the final 16 reversals. These yielded the points on a psychometric function at which the observer was .21 and .79 likely to report the dot outside of the perceived contour. We derived two measures from these inside and outside thresholds for each stimulus. *Imprecision* was defined as the difference between the inside and outside thresholds for a given shape. The greater this difference, the less precisely the interpolated contour could be localized. The other derived threshold measure yielded an estimate of where the occluded contour was perceived. *Location* was defined as the midpoint between the inside and outside thresholds, relative to the theoretical contour position (assuming completion as a perfect circle). We took this midpoint to be an estimate of the observer's .50 probability of an "outside" response, as would be the case if the psychometric function in the middle region approached linearity, or under the weaker condition that the psychometric function was rotationally symmetric around the .50 threshold. For the location measure, a negative value suggested that the observer perceived the interpolated contour to be inside of its theoretical position, whereas a positive value suggested that the observer perceived the contour to be outside of its theoretical position. A value of 0 indicated that the observer perceived the occluded contour to be in its exact theoretical position, with no distortion of the perceived shape.

The data from one observer were discarded because of an inability to perform the task (the staircases failed to converge). The location and imprecision data from the remaining 12 observers were analyzed by using repeated measures 2 × 2 ANOVAs with amount of occlusion and size as the independent variables. Additionally, planned *t* tests compared results for the smaller circle occluded by 32.5% with those for the larger circle occluded by 20.0% (which had the same absolute length of occluded contour).

Results and Discussion

Figure 10A graphs imprecision as a function of amount of occlusion and stimulus size. Clearly, occlusion level had a small but highly significant effect on imprecision, $F(1, 11) = 14.97$, $p < .01$, as did stimulus size, $F(1, 11) = 12.70$, $p < .01$; the interaction between these factors did not reach significance, $F(1, 11) = 2.43$, *ns*. In Figure 10B, imprecision is replotted as a function of absolute length of occluded contour. An examination of this graph suggests that a single factor—occluded contour length—may account for the observed variations in imprecision. In line with this idea, a *t* test revealed no significant difference in imprecision between the small circle with 32.5% contour occlusion and the larger circle with 20.0% contour occlusion, $t_{11} < 1$, *ns*, for which absolute contour length was matched.

In sum, precision of contour localization decreased slightly with increasing occlusion, but this result appears to be linked to the absolute length of the occluded contour rather than to the proportion of the shape that was occluded. A single edge interpolation process that completes partly occluded contours incrementally could account for this finding.

The suggestion of absolute contour length as the critical factor in determining precision may appear counterintuitive in light of previous experiments showing that interpolated contour strength depends on support ratio, not absolute gap size (e.g., Banton & Levi, 1992; Ringach & Shapley, 1996; Shipley & Kellman, 1992b). Assuming that our precision measure correlates with other

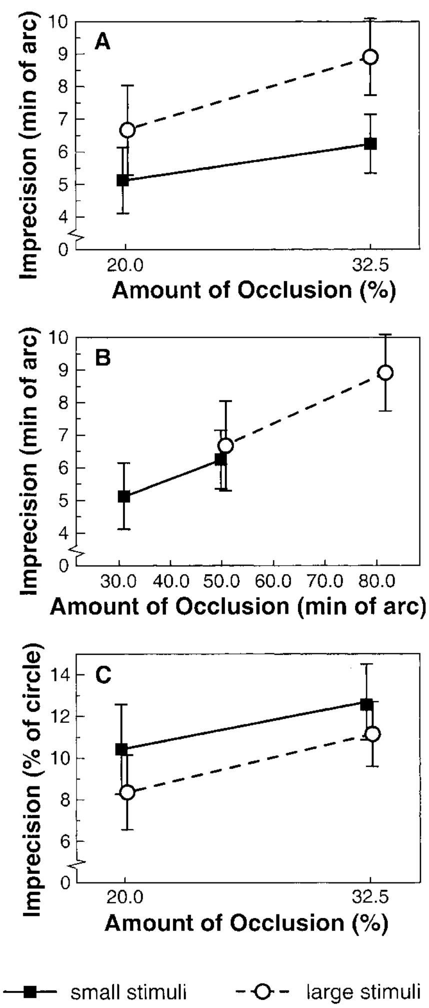

Figure 10. Precision results for Experiment 2. A: Imprecision as a function of amount of occlusion and stimulus size; B: imprecision as a function of absolute length of occluded contour; C: relative imprecision as a function of amount of occlusion and stimulus size (i.e., imprecision values presented as a percentage of circle diameter). Higher values on these graphs indicate a "fuzzier" contour. Error bars represent plus or minus one standard error of the mean across observers.

measures of contour strength, one might therefore expect equal precision of contour localization for shapes with the same percentage of contour occlusion, regardless of overall stimulus size. However, edge processing—and presumably contour interpolation—depends on combining information across multiple spatial frequency channels (e.g., Marr & Hildreth, 1980; Morrone & Burr, 1988; see also Kellman et al., 2001). Thus, the precision of interpolated contour representations might be expected to scale with stimulus size, as different channels may assume principal responsibility for processing. To examine this hypothesis, we rescaled the precision data by dividing each precision value by the diameter of the occluded circle. Figure 10C plots the results with these relative units. As can be seen, differences in precision due to stimulus size were greatly reduced and no longer reached significance, $F(1, 11) = 4.01$, $p = .07$. The remaining difference, whereby the *smaller* stimuli receive somewhat less precise contour representations than expected, may be due to the way in which the visual system pools information across spatial frequency channels; further research is needed to clarify this effect. Nonetheless, precision—when considered in relative units—correlates with other measures of interpolated contour strength in that it depended primarily on proportion of occluded contour (which is complementary to support ratio), rather than on absolute stimulus size.

Perceived contour location, plotted as a function of amount of occlusion and stimulus size, appears in Figure 11A. To reiterate, positive values on this graph indicate perception of the occluded contour as outside of its theoretical position and negative values indicate perception of the occluded contour as inside of its theoretical position. Both amount of occlusion, $F(1, 11) = 75.75$, $p < .001$, and stimulus size, $F(1, 11) = 17.08$, $p < .01$, had a significant effect on perceived contour location; the interaction between these factors also reached significance, $F(1, 11) = 13.33$, $p < .01$.

At first glance, the effect of stimulus size, as well as the interaction, suggests that observers perceived contour location differently for the two different display sizes. However, this is true only if retinal distance is the appropriate metric for measuring error of location. An alternative interpretation of these data may be that interpolation at both scales followed a similar shape for a given amount of occlusion, relative to the whole figures. Just as with precision, we examined this idea by rescaling the contour location data by dividing each location value by the diameter of the occluded circle. The results of this analysis appear in Figure 11B. When considered in these relative units, differences in location due to stimulus size largely disappeared. An ANOVA with these rescaled units revealed no main effect of size, $F(1, 11) = 2.70$, *ns*, although the interaction, while small, remained statistically reliable, $F(1, 11) = 22.74$, $p < .01$. More interesting, amount of occlusion still had a highly significant effect in these relative units, $F(1, 11) = 77.71$, $p < .001$. It appears that observers consistently completed the circles occluded by 20.0% as slightly "stretched" relative to a perfect circle, $t_{11} = 2.32$, $p < .05$, and the circles occluded by 32.5% as "flattened," $t_{11} = 8.08$, $p < .001$.

This significant distortion of shape, particularly of the more highly occluded objects, suggests that perception did not depend on a process of recognition from partial information without perceptual completion of edge information. Such a process would be predicted to produce poor precision on this task, but not to introduce a systematic location error, consistent across observers. However, further examination of this effect is required to determine whether a single edge interpolation process or multiple processes underlie the different distortions of contour shape seen with the different amounts of occlusion.

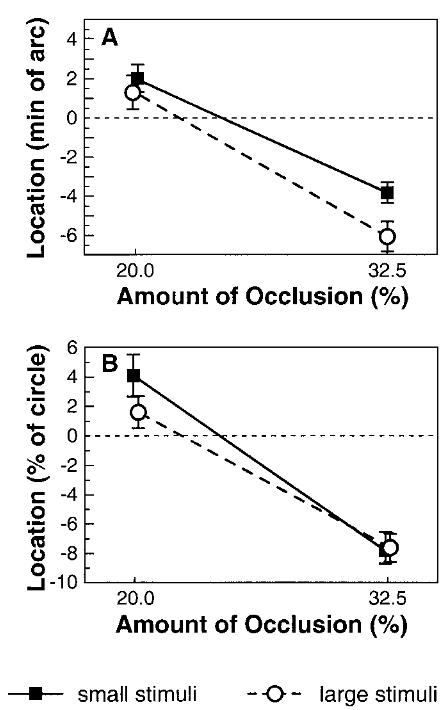

Figure 11. Location results for Experiment 2. A: Perceived contour location as a function of amount of occlusion and stimulus size; B: level of shape distortion as a function of amount of occlusion and stimulus size (i.e., location results presented as a percentage of circle diameter). On these graphs, positive values indicate perception of the contour as outside its theoretical location and negative values indicate perception of the contour as inside its theoretical location. Error bars represent plus or minus one standard error of the mean across observers.

Experiment 3

Experiment 2 demonstrated that precision of contour localization decreases slightly but significantly with increasing contour occlusion; this finding is consistent with a single edge interpolation process operating on objects with both 20.0% and 32.5% contour occlusion. On the other hand, the location data revealed qualitatively different distortions in contour shape for the different amounts of occlusion, a finding that may be indicative of different underlying processes. In this final experiment, we used the dot-localization paradigm to compare the final representations of objects with amounts of occlusion ranging from 10.0% to 35.0%. If a single edge interpolation process operates across this entire range of occlusions, then contour location and precision should vary smoothly with amount of occlusion. By contrast, if the completion of moderately occluded objects versus the completion of highly occluded objects depends on qualitatively different completion mechanisms, then a sudden break in location and precision values might be expected at the point where the amount of occlusion exceeds the spatial limit of the basic edge interpolation mechanism. For this experiment, the boundary in question may be 25.0%—the limit of relatability for circles.

Method

Twenty UCLA undergraduate students (14 women and 6 men), none of whom participated in the other experiments, acted as observers for the third experiment. Observers ranged in age from 18 to 27 (mean age = 20.4 years). As before, observers had normal or corrected-to-normal vision, were unaware of the experimental hypothesis, and received partial course credit for their participation.

The experimental stimuli and procedure were identical to that of the second experiment except (a) six amounts of contour occlusion were tested (10.0%, 15.0%, 20.0%, 25.0%, 30.0%, and 35.0%) and (b) only the smaller stimuli were used.

The data from 1 observer were discarded because one staircase failed to converge within a 1-hr session. Location and imprecision data from the remaining observers were submitted to a repeated measures ANOVA with amount of occlusion as the independent variable.

Results and Discussion

Figure 12 plots imprecision as a function of the amount of contour occlusion. Clearly, imprecision of contour localization depended on the amount of occlusion, $F(5, 90) = 23.86$, $p < .001$. With increasing occlusion, imprecision of contour location increased linearly, $F(1, 18) = 117.17$, $p < .001$; the linear fit shown in Figure 12 accounts for 96.0% of the variance in the mean imprecision values. Moreover, the highly significant linear trend cannot be attributed to a sudden change in precision levels occurring in slightly different places for different observers; an examination of individual observers' data revealed no consistent nonlinearity.

In short, we see no evidence of a sudden change in the precision of completed contours as the level of occlusion rises beyond 25.0% (the limit of relatability) or any other spatial limit. Rather, observers gradually and systematically became less precise with increasing occlusion. The idea that a single contour interpolation process underlies shape completion across the tested range of occlusions provides the most parsimonious explanation for this result.

The location data further strengthen this conclusion. Figure 13 depicts the change in perceived contour location as a function of amount of occlusion. As occlusion increased, perceived contour location shifted slightly but systematically from being seen as outside at 10.0% occlusion to inside at 35.0% occlusion, $F(5, 90) = 36.92$, $p < .001$. The linear trend was highly significant, $F(1, 18) = 53.32$, $p < .01$, accounting for 97.9% of the variance in the mean location values. Individual observers varied considerably with regard to the amount of occlusion leading to the most accurately localized contour, but consistently showed this inward trend with increasing occlusion.

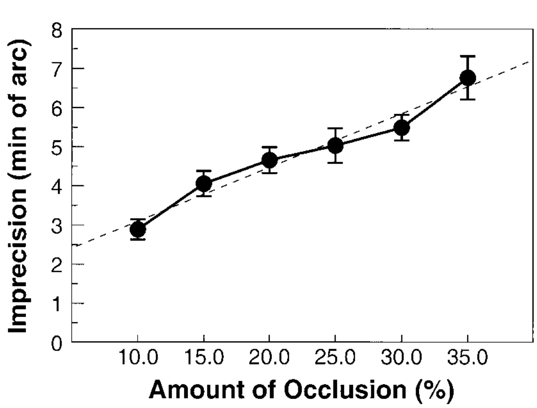

Figure 12. Precision results for Experiment 3: imprecision as a function of amount of occlusion. Higher values on this graph indicate a "fuzzier" contour. Error bars represent plus or minus one standard error of the mean across observers. The dotted line shows the best linear fit, which accounts for 96.0% of the variance in the means.

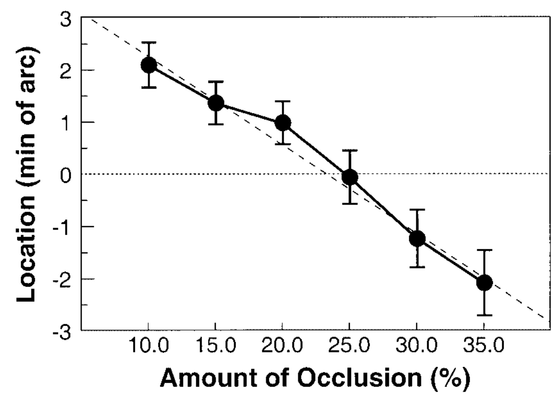

Figure 13. Location results for Experiment 3: perceived contour location as a function of amount of occlusion. Positive values indicate perception of the contour as outside its theoretical location and negative values indicate perception of the contour as inside its theoretical location. Error bars represent plus or minus one standard error of the mean across observers. The dotted line shows the best linear fit, which accounts for 97.9% of the variance in the means.

The reason for the systematic change in the *accuracy* of dot localization is somewhat unclear. These data may indicate that the contour interpolation process is not entirely local, taking into account the broader stimulus context as well as the physically specified edges leading into the occluder (see also Sekuler, 1994; Sekuler & Murray, 2001; Sekuler et al., 1994). For example, contour location appears to shift in the direction of the center of mass of the entire stimulus. However, the fact that perceived contour location shifted systematically throughout the range of tested occlusions adds credence to the idea that the same completion process operates on all of the objects in question. Furthermore, this process appears to be an interpolation mechanism per se, rather than recognition from partial information. A "complete" representation achieved via encoding only of visible areas may be of variable precision, but the resulting contour location should not vary systematically with amount of occlusion.

General Discussion

The results of Experiment 1 support and extend previous studies indicating that completion time rises with amount of occlusion (Rauschenberger & Yantis, 2001; Shore & Enns, 1997). Specifically, this experiment shows that, consistent with phenomenal experience, the visual system can complete at least some highly occluded objects. However, the completion of highly occluded objects requires more extensive processing than objects occluded by lesser amounts. This latter finding fits nicely with previous evidence suggesting that time to completion varies with contextual stimulus factors (e.g., Bruno et al., 1997; Murray et al., 2001).

Experiments 2 and 3 suggest that the same contour interpolation process operates on highly occluded objects and on objects occluded by lesser amounts. The final edge representations of partly occluded circles varied gradually and systematically over the entire range of tested occlusions. No break in precision or accuracy of contour location occurred at 25.0% occlusion, a spatial limit suggested by relatability theory (e.g., Kellman & Shipley, 1991, 1992) and consistent with previous empirical results (Rauschenberger & Yantis, 2001; Shore & Enns, 1997). Although this systematic variation cannot conclusively rule out the operation of different processes for the completion of objects occluded by different amounts, parsimony suggests a single underlying process.

Together, the results of this study suggest that visual completion processes can operate at levels of occlusion that exceed the spatial limit implied by relatability theory's monotonicity constraint. Furthermore, variations in time to completion do not appear to reflect a spatial limit in the operation of low-level interpolation mechanisms. Instead, time to completion rises with amount of occlusion due to temporal variations in the processing of basic interpolation mechanisms.

These findings have clear implications for our understanding of contour interpolation mechanisms, including the bounding spatial conditions suggested by Kellman and Shipley's (1991, 1992) relatability criteria. We found no evidence that spatial factors limit either basic contour interpolation mechanisms or visual completion more broadly defined. Experiment 1 demonstrated the completion of objects with 32.5% contour occlusion, corresponding to 41.5% area occlusion for the circles and 35.6% area occlusion for the squares. Given enough time, the visual system can develop complete representations of highly occluded objects, even when the visible contours are nonrelatable. Thus, relatability criteria, as originally defined, do not universally specify the spatial limits of visual completion processes.

This is not to suggest, however, that spatial factors in no way constrain visual completion. Obviously, the visual system needs some minimum amount of physically specified sensory input to guide interpolation. According to Kellman and Shipley (1991, 1992), contour completion specifically requires that the visible edges leading into the occluder are relatable—connectable with a smooth, monotonic contour. Some aspects of our results are consistent with this notion. For example, the amount and configuration of contour information, rather than visible surface area, appear to be the primary determinants of how completion processes proceed; we found no significant differences between the processing of circles and squares with the same amount of contour occlusion, but different amounts of area occlusion. Furthermore, the dot-localization experiments indicated that with increasing occlusion and, thus, decreasing relatability, the completed contours of partly occluded circles became less precisely defined. However, other aspects of our findings present a clear challenge to Kellman and Shipley's (1991, 1992) original theory. Specifically, our findings violate the relatability principle in showing that circles with 32.5% contour occlusion can be completed; these shapes are not relatable because the tangent extensions of their visible edges meet at less than a 90° angle and thus cannot be completed with a monotonic contour.

Clearly, our data indicate a need to modify the "90 degree rule" implied by relatability theory's monotonicity constraint (Kellman & Shipley, 1991, 1992). We suggest that the precision with which completed contours are represented does decrease with curvature, as Kellman and Shipley's (1991, 1992) original theory suggests. However, we further propose that the exact point at which contour interpolation mechanisms break down is not always 90°, but varies with context—stimulus factors other than the relative position of inducing edges. According to this "flexible 90 degree principle," a 90° limit may apply to cases in which contextual stimulus factors remain neutral with regard to whether completion should occur (e.g., an unfamiliar, asymmetric shape with simple, smoothly varying edges). However, when contextual factors favor visual form completion, completion mechanisms may produce interpolated contours that bend through more than 90° (as in the current experiments). By contrast, when contextual factors interfere with visual form completion, even 90° completions may be prohibited (e.g., Field et al., 1993).

In the current study, several contextual factors may have enhanced the completion of objects occluded by small amounts and allowed the completion of objects that exceeded the strict limit of relatability. First, the completed shapes in question were circles, and thus processes based on familiarity (e.g., Kanizsa & Gerbino, 1982) and global symmetry (Boselie, 1994; Sekuler, 1994; Sekuler et al., 1994; van Lier & Wagemans, 1999) may have interacted with low-level contour interpolation mechanisms. Second, the visual system may take curvature into account in determining contour connectedness (Takeichi, Nakazawa, Murakami, & Shimojo, 1995). That is, the shape of the contours leading into the discontinuities, in addition to the instantaneous tangents at the points of occlusion, may be important for guiding edge interpolation. Third, the completion of the highly occluded circles accomplished contour closure; the importance of closure in strengthening edge perception processes has been demonstrated in several studies (Kovács & Julesz, 1993; Pettet, McKee, & Grzywacz, 1998). Although not relevant to the current experiment, stereo depth cues consistent with the depth ordering of the occluded shape and its occluder also might extend the point at which completion processes break down (e.g., Bruno et al., 1997). By contrast, high overall stimulus complexity may reduce the spatial limit of contour interpolation processes (e.g., Field et al., 1993). Further research with a more varied range of stimuli may uncover yet other factors that influence the spatial limits of contour interpolation.

While discussing spatial limitation, we might also consider whether the amount of physically specified information should be considered in absolute or relative terms. Experiment 2 indicated that asymptotic precision of dot location depended on absolute occluded contour length, not proportion of contour occlusion. However, previous studies showed that interpolated contour strength depends on support ratio (akin to proportion of occlusion in our study; Banton & Levi, 1992; Ringach & Shapley, 1996; Shipley & Kellman, 1992b). Moreover, relatability constraints, even when modified as above, imply that the occluded region must be considered in relation to the overall shape. However, these issues may not be at odds with the current results. In Experiment 2, equal proportions of occlusion gave rise to comparable precision of dot-localization when precision values were rescaled by dividing each datum by the diameter of the occluded circle. When applied to location, this analysis revealed the perceived shape of the interpolated contour; similarly, the relative precision measure resulting from this analysis revealed how much variation occurred in the interpolated contour's shape. This relative precision measure may, in fact, correspond to measures of perceived contour strength used in other studies (e.g., Banton & Levi, 1992; Shipley & Kellman, 1992a, 1992b). An interpolated contour that can be localized to within 5 min of arc (for example), would seem quite sharp (or "strong") if it belonged to a partly occluded shape that fills the visual field, but extremely fuzzy (or "weak") if the occluded shape to which it belonged was itself only 10 min of arc across. Thus, whereas absolute gap size may be crucial for the operation of underlying contour interpolation mechanisms, our subjective experience of interpolated contours and surfaces—including whether a shape becomes completed and how clearly the resulting shape appears to be defined—may depend more on a relative measure of amount of occlusion.

In addition to clarifying issues of spatial limitation, the current study adds to our understanding of the mechanisms underlying the completion of partly occluded objects. For one thing, the processes leading to the completed representations in this study appear to be interpolation mechanisms per se, rather than recognition from partial information. Furthermore, this study bolsters the finding that interpolation mechanisms require more time to operate as the amount of occlusion rises. Our results specifically indicate that contour interpolation processes vary with level of occlusion, although surface spreading may also have contributed to the observed completion times.

How might these contour interpolation processes best be characterized? As discussed previously, contour completion may be explained by the processing of an interactive network of orientation-signaling units (e.g., Field et al., 1993). That is, completion may depend on the successive activation of adjacent edge-sensitive neurons via facilitative horizontal interactions. Recent experiments with illusory contours provide support for this approach to contour interpolation (e.g., Pillow & Rubin, 2002). Similarly, a gradual "surface-spreading" process could account for the interpolation of surface information (Yin et al., 1997, 2000). Although the experiments reported herein were not designed to distinguish among interpolation models, the consistency of our findings with network-style theories of completion should be noted. If we assume that the spread of activation for contour and surface completion occurs gradually and incrementally, then the completion of objects with greater amounts of occlusion should require a more prolonged spread of activation, and thus increased time to completion.

Network-style interpolation mechanisms may also account for several other findings of the current study. First, our priming experiment found no evidence for an initial mosaic representation prior to completion. This result converges with other experiments using the primed-matching paradigm (Bruno et al., 1997; Sekuler & Palmer, 1992, Experiment 3), although a mosaic representation has been found in cases in which the primes and probes appear in the same retinotopic position (Sekuler & Palmer, 1992, Experiment 2) and in some experiments using different paradigms (e.g., Murray et al., 2001). Taken together, these studies suggest that occluded objects may initially be represented as mosaics, at least in some circumstances, but that the representations begin to evolve toward completion almost immediately. Indeed, network models of interpolation predict a rapid initiation of completion processes.

Second, we found that when partly occluded representations met the criteria for completion, the levels of priming were slightly, but consistently, lower for the partly occluded primes than for the complete primes (although, statistically, the values did not differ). Accordingly, the highest completion index obtained for either 20.0% or 32.5% occlusion at any duration was .86. Furthermore, the priming levels (and the completion index) reached asymptote for both prime types, so there is no reason to suspect that the small, consistent difference between occluded and complete representations would disappear at even longer SOAs. The observed completion index values clearly suggest that the visual system treats occluded objects as effectively complete, but they also imply that some representational difference between occluded and unoccluded objects is maintained. In the context of interactive network models, this finding follows from the fact that units representing occluded information do not receive direct input and thus become less strongly activated than units representing physically defined surface elements or contours. The weaker representation of partly occluded regions, as compared with visible regions, may well account for the completion indices being less than one.

Third, as shown in Figure 14, network models may explain the dot-localization results whereby the final representations of partly occluded contours became less precise with increasing occlusion. In short, because contour completion depends on the *successive* facilitation of neural units, the final activation levels of units corresponding to a partly occluded contour should decrease with increasing distance from physically specified edges. Moreover, in addition to strongly facilitating the unit that continues the collinear or co-circular path (Kellman, Shipley, Garrigan, & Guttman, 2003), each active neuron may weakly facilitate several proximal units that deviate slightly from the path; thus, the total number of activated units will multiply with distance from physically specified edges. This combination of decreased activity within each unit and increased number of active units may correspond to a less precisely specified contour. Therefore, more highly occluded contours, the centers of which have greater distance from luminance edges, receive "fuzzier" representations than contours occluded by smaller amounts.

Finally, as discussed above, Experiment 2 suggested that asymptotic precision of dot location depends on absolute, not relative, occluded contour length. Within each spatial channel of an interactive network, absolute distance from physically specified edges (and thus absolute gap size) should be the primary determinant of the activation level and number of active neurons in the occluded region. Further work is needed to determine how the visual system combines this information across multiple spatial frequency channels to achieve a contour representation of some measurable precision. Regardless, support ratio should have little impact on neural activations or the ultimate precision of an interpolated contour, provided that visible contours are of sufficient length to facilitate adjacent neurons strongly.

Conclusion

This study provides the first definitive evidence for the completion of highly occluded objects—those missing more than 25.0% of the bounding contour—and confirms the finding that time to completion rises with amount of occlusion. The experiments reported herein also demonstrate that a single contour interpolation mechanism can account for shape completion in objects with very different levels of occlusion, even when occlusion renders the contours nonrelatable. Thus, relatability criteria (Kellman & Shipley, 1991, 1992) do not impose a universal spatial limit on the operation of contour completion mechanisms. As such, the observed variations in completion time can be attributed to variations in the operation of these low-level interpolation mechanisms rather than to the deployment of additional processes. Current theories of visual completion need to be assessed in light of the fact that

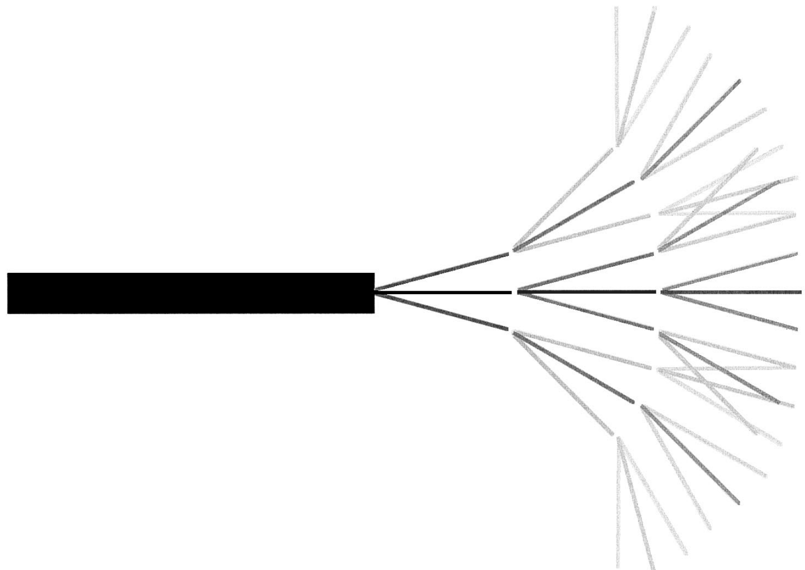

Figure 14. Simplified diagram of the activation pattern for a network model of contour interpolation. The black bar represents the luminance edge that initiates the spread of activation. Each line represents the orientation and location of an active neuron, and the contrast of the line represents the level of activation (i.e., darker lines indicate more activity). Each neuron strongly facilitates the unit that continues the collinear or co-circular path, but also weakly facilitates off-path units. With increasing distance from the luminance edge, the number of active neurons increases but the activation within each neuron decreases.

stimulus variables, including amount of occlusion and the spatial arrangement of visible contours, affect the time course of low-level interpolation processes, as well as whether interpolation occurs at all.

References

Banton, T., & Levi, D. M. (1992). The perceived strength of illusory contours. *Perception & Psychophysics, 52,* 676–684.

Behrmann, M., Zemel, R. S., & Mozer, M. C. (1998). Object-based attention and occlusion: Evidence from normal participants and a computational model. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1011–1036.

Beller, H. K. (1971). Priming: Effects of advance information on matching. *Journal of Experimental Psychology, 87,* 176–182.

Boselie, F. (1994). Local and global factors in visual occlusion. *Perception, 23,* 517–528.

Bruno, N., Bertamini, M., & Domini, F. (1997). Amodal completion of partly occluded surfaces: Is there a mosaic stage? *Journal of Experimental Psychology: Human Perception and Performance, 23,* 1412–1426.

Cohen, J., MacWhinney, B., Flatt, M., & Provost, J. (1993). PsyScope: An interactive graphic system for designing and controlling experiments in the psychology laboratory using Macintosh computers. *Behavior Research Methods, Instruments, & Computers, 25,* 257–271.

Davis, G., & Driver, J. (1998). Kanizsa subjective figures can act as occluding surfaces at parallel stages of visual search. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 169–184.

Derman, C. (1957). Non-parametric up-and-down experimentation. *Annals of Mathematical Statistics, 28,* 795–797.

Elder, J., & Zucker, S. (1993). The effect of contour closure on the rapid discrimination of two-dimensional shapes. *Vision Research, 33,* 981–991.

Field, D. J., Hayes, A., & Hess, R. F. (1993). Contour integration by the human visual system: Evidence for a local "association field." *Vision Research, 33,* 173–193.

Gegenfurtner, K. R., Brown, J. E., & Rieger, J. (1997). Interpolation processes in the perception of real and illusory contours. *Perception, 26,* 1445–1458.

Gerbino, W., & Salmaso, D. (1987). The effect of amodal completion on visual matching. *Acta Psychologica, 65,* 25–46.

Gold, J. M., Murray, R. F., Bennett, P. J., & Sekuler, A. B. (2000). Deriving behavioural receptive fields for visually completed contours. *Current Biology, 10,* 663–666.

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

Guttman, S. E., & Kellman, P. J. (2002). Do spatial factors influence the microgenesis of illusory contours? *Journal of Vision, 2,* 355a.

He, Z. J., & Nakayama, K. (1992, September 17). Surfaces versus features in visual search. *Nature, 359,* 231–233.

He, Z. J., & Nakayama, K. (1994a). Perceived surface shape not features determines correspondence strength in apparent motion. *Vision Research, 34,* 2125–2135.

He, Z. J., & Nakayama, K. (1994b). Perceiving textures: Beyond filtering. *Vision Research, 34,* 151–162.

Heitger, F., von der Heydt, R., Peterhans, E., Rosenthaler, L., & Kübler, O. (1998). Simulation of neural contour mechanisms: Representing anomalous contours. *Image and Vision Computing, 16,* 407–421.

Kanizsa, G., & Gerbino, W. (1982). Amodal completion: Seeing or thinking? In J. Beck (Ed.), *Organization and representation in perception* (pp. 167–190). Hillsdale, NJ: Erlbaum.

Kellman, P. J. (2000). An update on Gestalt psychology. In B. Landau, J. Jonides, E. Newport, & J. Sabini (Eds.), *Essays in honor of Henry and Lila Gleitman* (pp. 157–190). Cambridge, MA: MIT Press.

Kellman, P. J., Guttman, S. E., & Wickens, T. D. (2001). Geometric and neural models of object perception. In T. F. Shipley & P. J. Kellman

(Eds.), *From fragments to objects: Segmentation and grouping in vision* (pp. 183–245). New York: Elsevier.

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

Kellman, P. J., & Shipley, T. F. (1992). Perceiving objects across gaps in space and time. *Current Directions in Psychological Science, 1,* 193–199.

Kellman, P. J., Shipley, T. F., Garrigan, P. B., & Guttman, S. E. (2003). *Arclets: A network model of visual interpolation.* Manuscript in preparation.

Kellman, P. J., Shipley, T. F., & Kim, J. (1996, November). *Global and local effects in object completion: Evidence from a boundary localization paradigm.* Paper presented at the 37th Annual Meeting of the Psychonomic Society, Chicago, IL.

Kellman, P. J., Temesvary, A., Palmer, E. M., & Shipley, T. F. (2000). Separating local and global processes in object perception: Evidence from an edge localization paradigm. *Investigative Ophthalmology & Visual Science, 41,* S741.

Kellman, P. J., Yin, C., & Shipley, T. F. (1998). A common mechanism for illusory and occluded object completion. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 859–869.

Keppel, G., & Saufley, W. H., Jr. (1980). *Introduction to design and analysis: A student's handbook.* New York: Freeman.

Kovács, I., & Julesz, B. (1993). A closed curve is much more than an incomplete one: Effect of closure in figure–ground segmentation. *Proceedings of National Academy of Sciences USA, 90,* 7495–7497.

Marr, D., & Hildreth, E. (1980). Theory of edge detection. *Proceedings of the Royal Society of London, Series B, 207,* 187–217.

Moore, C. M., Yantis, S., & Vaughan, B. (1998). Object-based visual selection: Evidence from perceptual completion. *Psychological Science, 9,* 104–110.

Morrone, M. C., & Burr, D. C. (1988). Feature detection in human vision: A phase-dependent energy model. *Proceedings of the Royal Society of London, Series B, 235,* 221–245.

Murray, R. F., Sekuler, A. B., & Bennett, P. J. (2001). Time course of amodal completion revealed by a shape discrimination task. *Psychonomic Bulletin & Review, 8,* 713–720.

Pettet, M. W., McKee, S. P., & Grzywacz, N. M. (1998). Constraints on long range interactions mediating contour detection. *Vision Research, 38,* 865–879.

Pillow, J., & Rubin, N. (2002). Perceptual completion across the vertical meridian and the role of early visual cortex. *Neuron, 33,* 805–813.

Pratt, J., & Sekuler, A. B. (2001). The effects of occlusion and past experience on the allocation of object-based attention. *Psychonomic Bulletin & Review, 8,* 721–727.

Rauschenberger, R., & Yantis, S. (2001, March 15). Masking unveils pre-amodal completion representation in visual search. *Nature, 410,* 369–372.

Rensink, R. A., & Enns, J. T. (1998). Early completion of occluded objects. *Vision Research, 38,* 2489–2505.

Ringach, D. L., & Shapley, R. (1996). Spatial and temporal properties of illusory contours and amodal boundary completion. *Vision Research, 36,* 3037–3050.

Rosch, E. (1975a). Cognitive representations of semantic categories. *Journal of Experimental Psychology: General, 104,* 192–233.

Rosch, E. (1975b). The nature of mental codes for color categories. *Journal of Experimental Psychology: Human Perception and Performance, 1,* 303–322.

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

Sekuler, A. B., & Murray, R. F. (2001). Amodal completion: A case study in grouping. In T. F. Shipley & P. J. Kellman (Eds.), *From fragments to objects: Segmentation and grouping in vision* (pp. 265–293). New York: Elsevier.

Sekuler, A. B., & Palmer, S. E. (1992). Perception of partly occluded objects: A microgenetic analysis. *Journal of Experimental Psychology: General, 121,* 95–111.

Sekuler, A. B., Palmer, S. E., & Flynn, C. (1994). Local and global processes in visual completion. *Psychological Science, 5,* 260–267.

Shipley, T. F., & Kellman, P. J. (1990). The role of discontinuities in the perception of subjective figures. *Perception & Psychophysics, 48,* 259–270.

Shipley, T. F., & Kellman, P. J. (1992a). Perception of partly occluded objects and illusory figures: Evidence for an identity hypothesis. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 106–120.

Shipley, T. F., & Kellman, P. J. (1992b). Strength of visual interpolation depends on the ratio of physically specified to total edge length. *Perception & Psychophysics, 52,* 97–106.

Shore, D. I., & Enns, J. T. (1997). Shape completion time depends on the size of the occluded region. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 980–998.

Takeichi, H., Nakazawa, H., Murakami, I., & Shimojo, S. (1995). The theory of the curvature-constraint line for amodal completion. *Perception, 24,* 373–389.

van Lier, R., & Wagemans, J. (1999). From images to objects: Global and local completions of self-occluded parts. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1721–1741.

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

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

Received 1996
Revision received May 29, 2003
Accepted June 10, 2003 ■