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# Shape Completion Time Depends on the Size of the Occluded Region

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Observers made speeded discriminations of whole, occluded, and mosaic shapes. Shape matching times increased with the amount of occluded shape (Experiment 1), as did the time to merely discriminate 2 shapes (Experiments 2–4). By contrast, the time to judge the shape of the visible portion decreased with larger occluded regions (Experiments 5–7). Experiments 3 and 6 used motion parallax to show that different perceptual operations are involved in discriminating occluded versus mosaic shapes. Experiments 4 and 7 showed that shape completion was unaffected by spatial attention. Results suggest that shape completion is a rapid and obligatory aspect of perception. However, they also show that the time course of completion varies with the size of the hidden region.

Humans, among other animals, are able to act rapidly on purely visual input. A major problem that has been overcome in accomplishing this feat concerns the indeterminacy of two-dimensional (2-D) images on the retina. That is, any image provides only partial information about the scene: Views of some objects are partly occluded by other objects, and some parts of every object are occluded by other parts of the same object. Nonetheless, the visual systems of mice (Kanizsa, Renzi, Conte, Compostela, & Guerani, 1993), newborn chicks (Regolin & Vallortigara, 1995), and human infants (Kellman & Spelke, 1983) are exquisitely prepared to deal with this problem, allowing them to behave toward partly occluded objects as though they were completely visible. In this research we explored the spatial nature of this process: Is the perceptual completion process influenced by the size of the occluded region?

The completion of edges and surfaces behind occluding objects is only one instance of a larger family of phenomena in which the visual system "goes beyond the information given" in a local region of the visual field. Others include a "filling in" of the retinal blindspot (Ramachandran, 1992), a "filling in" of real and artificially induced scotomas (Ramachandran & Gregory, 1991), and the perception of phantom motion (Brown & Weisstein, 1988) and subjective contours (Kanizsa, 1979). What makes completion behind occlusion unique is that it is not associated with any visible percept. As such, it is often referred to as amodal completion to emphasize the paradox of the experience of a complete object despite the absence of any visible contours behind the occluder.

In this article we use the term *shape completion*, even though we are concerned solely with completion behind occluders. This is consistent with the practice of some researchers who believe that there is much in common in the underlying mechanisms of *modal* (e.g., subjective contours) and *amodal* completion (Grossberg, 1994; Kellman & Shipley, 1991). However, other independent reasons include that the term does not communicate readily to researchers in other fields and that it has become, in our opinion, unnecessarily theory laden.

We also must warn at the outset that there are several important issues concerning shape completion on which there is little consensus. For instance, it is not clear how shape completion is related to the depth ordering of surfaces (Rensink & Enns, in press; Yonas, Craton, & Thompson, 1987). That is, shape segmentation without any explicit depth ordering may be sufficient to trigger shape completion mechanisms (e.g., Grossberg, 1994); alternatively, an initial depth ordering of surfaces might be a requisite step before shape segmentation and completion can occur (e.g., Nakayama, Shimojo, & Silverman, 1989). There also is controversy on the "completeness" of shape completion, that is, whether only minimal edge continuation has occurred behind an occluder (e.g., Minguzzi, 1987) or whether the hidden shape has been richly elaborated with continuous edges and internal color (e.g., Grossberg, 1994). We remain neutral on these issues in this article.

## Background Research

Much of the classical research on shape completion was based on introspective reports, which noted that partly occluded shapes never appeared fragmented in consciousness, that their apparent shape seemed to be instantaneously available, and that prior knowledge seemed not to influence their perceived shape (Kanizsa, 1979; Koffka, 1935; Michotte, Thinès, & Crabbé, 1967). Gestalt psychologists used these reports to argue that shape completion was one of the

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most primitive operations involved in the organization of a stimulus.

More recent support for these observations has been based on measures of performance. For instance, Weisstein (1970) presented observers with one of four stimuli in an adaptation phase: a grating, a grating partly occluded by a cube, a cube alone, and a gray field equal in luminance to the grating. Compared with the cube alone or the gray field, subsequent contrast discrimination was depressed for the grating condition and, to a lesser extent, for the occluded grating. This suggested a mechanism that completed the grating behind the cube, thereby influencing contrast discrimination in a manner similar to the complete grating.

Other investigators have used visual search (Enns & Rensink, 1992; Rensink & Enns, in press) and texture segmentation tasks (He & Nakayama, 1992). For example, observers searched in one condition for a square that was occluded partly by a disk that had been placed among whole squares and other disks (Rensink & Enns, in press). In another condition, a notched square was again the target, but this time there was no disk to fill in the missing part. Visual search times increased markedly with display size in the first condition, averaging more than 30 ms per item, whereas search times in the second condition exhibited pop-out, changing little with display size. This suggests that local cues to occlusion (e.g., T-junctions) are taken into account at the same early stages that govern pop-out for simple image features such as color and orientation.

Shape completion therefore appears to be primitive in several senses, including that of comparative phylogenesis, ontogenesis, and perceptual microgenesis, and it is insulated from the intentions of an observer. As such, its characteristics sometimes have proved to be elusive. Consider the seemingly straightforward question of how much time is required for shape completion to occur. In one study (Gerbino & Salmaso, 1987), adult observers were asked to match shapes as "same" or "different." Response time (RT) to whole and partly occluded shapes did not differ, whereas responses for mosaic shapes (i.e., retinally equivalent to the occluded shapes but involving no cues to occlusion) were much slower. The authors concluded that "completion is better conceived as the product of an automatic transformation within the visual code, which is so fast that we have been unable to measure its duration" (Gerbino & Salmaso, 1987, p. 42).

Other researchers have measured the time course of completion using a repetition priming task (Sekuler & Palmer, 1992). Observers were first shown a whole, occluded, or mosaic shape (primes). After a variable interval, they were asked to make a same–different decision on pairs of whole or mosaic shapes (probes). For whole and mosaic primes, the expected advantages were found, with responses being faster when the same shapes were probed. However, for occluded shapes, an interesting interaction occurred with time. For intervals under 200 ms, responses were faster to mosaic probes; for longer intervals, they were faster to whole probes, suggesting that it takes at least 200 ms for a completed shape representation to be formed.

Bruno, Bertamini, and Domini (in press) reported a replication of these findings for pictorial displays. However, they also found that the additional depth cue of binocular parallax allowed more rapid responses to whole probes than mosaic probes at intervals as short as 100 ms. This suggests that observers have early access to a completed shape if the depth cues in the display are sufficiently rich.

## Scope of the Current Research

How general are these conclusions? We began by noting that shape completion is an inherently spatial process (i.e., some portion of a shape or an edge is interpolated) and that the time course of completion might therefore be intimately related to this spatial variable. Does completing a larger portion of a shape take more time than completing a smaller portion? Or, is a fixed time required that is independent of the spatial variable? The answer is uncertain because previous studies have tended to use a single level of spatial occlusion.

The general strategy we used was to have observers perform a shape discrimination task while we randomly varied the amount of shape that was hidden by occlusion or removed in control "mosaic" shapes. The instructed task was to make a speeded discrimination of a target shape that was not formally related to whether the shape was occluded. Therefore, any influence of occlusion would be indirect or implicit, in that observers were not required to report directly on any perceived aspect of the missing shape region.

We examined performance on two kinds of tasks with similar stimuli. The first task (Experiments 1–4) biased observers to adopt a "constancy" mode of perception (Rock, 1983; i.e., a mode in which the shapes are assumed to have been completed). Here observers reported the shape of a target regardless of whether it was completely visible. If completion occurred for occluded shapes, it would benefit performance on them compared with mosaic shapes, despite there being no formal requirement to use the completed representation in the task. In the second task (Experiments 5–7) the problem was inverted by asking observers to adopt a "proximal" mode of perception (Rock, 1983). Here observers would have to access the retinal rather than the completed shape to answer correctly. If completion occurred, it would be evident in an interference effect for occluded shapes relative to the mosaic shapes. In both tasks, we also examined the influence of another cue to depth (motion parallax), as well as the relation between completion and spatial attention (covert orienting), to provide converging evidence on the characteristics of the shape completion process.

## Experiment 1

We began our investigation by replicating the matching task of Gerbino and Salmaso (1987), both with the level of occlusion they had used (about 3% of the shape) and with a much larger level (about 20%) that, to our subjective eyes, appeared to complete just as readily. If shape completion really is instantaneous (or at least below the measurement

threshold for RTs), the gap size variation shown in Figure 1 should have no influence: Whole and occluded shapes should be matched equally rapidly and much faster than mosaic shapes regardless of gap size. Alternatively, if completion time is sensitive to spatial area, we should be able to measure a difference between whole and occluded shapes at the larger gap size.

Following Gerbino and Salmaso (1987), we also tested displays to control for the hypothesis that RT would be slowed on mosaic shapes because of deep concavities. These were called "occluded mosaic distractors" (see the bottom row in Figure 1) because they were identical to the small-gap-occluded condition, except that the occluding item was itself now a mosaic shape that varied in gap size. Other minor changes included (a) adding control displays to test for interference effects from the nontarget item and (b) providing feedback to the observer on each trial.

## Method

*Observers.* Ten students (5 women, 1 of whom was left-handed, and 5 right-handed men) from the undergraduate subject pool at the University of British Columbia participated in return for extra course credit. All observers reported normal or corrected-to-normal vision.

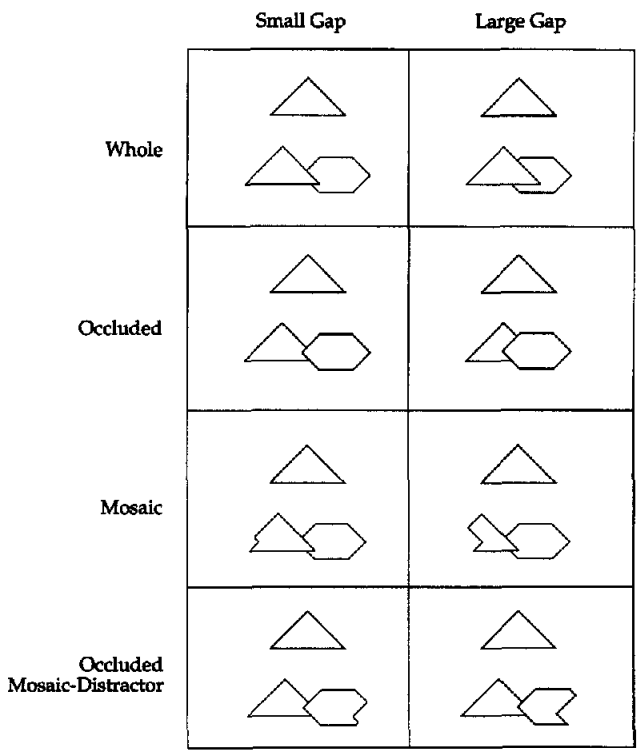


*Figure 1.* Examples of "same" displays used in Experiment 1. The target shape in each example is a triangle (upper), so it also appears as one member of the comparison set (lower). The actual vertical distance between the target and comparison set has been reduced by one half in this figure. The relative position of the two items in the comparison set was determined randomly, all three target shapes (triangles, hexagons, and diamonds) were used equally often, and one half of the displays contained no match ("different" trials).

*Stimuli and apparatus.* Display presentation and response recording was controlled by a Macintosh computer running VScope software (Enns & Rensink, 1992). Each display consisted of items presented 7° above and below fixation. The upper item was the target; the lower one was a comparison set of one or two items, as shown in Figure 1. Each item of the comparison set items was positioned randomly to the right or left of center. Display items consisted of diamonds (2.9° × 2.9°), triangles (3.8° × 1.9°), and hexagons (3.5° × 1.8°).

The comparison set of items varied both in stimulus type (whole, occluded, mosaic, and occluded mosaic distractor) and gap size (small and large). In addition, whole control stimuli were presented: either one item alone (single) or two items separated by 0.25° of visual angle (double). The degree of horizontal overlap was 0.3° in the small gap size (as in Gerbino & Salmaso, 1987) and 1.2° in the large gap size. The "different" stimuli were created by replacing the target item from a "same" trial with a shape that was different from any other in the display. Thus, on most "different" trials, three shapes were presented, two in the comparison set and one as the target. For the single control conditions, the two items were selected randomly from the possible three.

*Procedure.* The observer indicated with a keypress whether one of the comparison items was the same as the target. Observers were seated approximately 40 cm from the screen, which they viewed binocularly. The index finger used for same and different stimuli were counterbalanced across observers. Instructions emphasized the need to keep the eyes fixated at the center of the screen throughout a trial. Before testing, observers were shown pictures of occluded, whole, and mosaic versions of each shape and were told that for the purposes of the experiment, these should be considered the same shape. They also were explicitly instructed that some shapes would appear to be "missing a piece" but that these should be given the same response as a shape that could be seen in its entirety.

Observers were first given at least 15 trials of practice, continuing until they could perform 5 consecutive trials correctly. Observers then were tested on 600 trials (10 blocks of 60). The first block and the first three trials of every subsequent block were treated as practice and were not included in the analysis, leaving 513 trials for analysis from each observer.

Each display was presented for 200 ms. After an observer responded (or a maximum of 3 s had passed), a feedback symbol (plus or minus) was presented at the center of the screen for 915 ms. This served as the fixation point for the next trial, which was presented after a 750-ms interval in which the screen was blank.

## Results

The mean correct RTs and the mean percentage of errors on "same" trials are shown in Figure 2. The results from the occluded mosaic distractor shapes were included in the statistical analyses but are not shown in the graph because they did not differ from the small-gap-occluded shapes. Also note that "different" trials were not analyzed because they involved a more complex task analysis (Gerbino & Salmaso, 1987). Nonetheless, we noted that they showed a pattern similar to the "same" trials shown here.

RTs and errors were each analyzed with a repeated measures analysis of variance (ANOVA) for gap size (none, small, and large) and stimulus type (whole, occluded, mo-

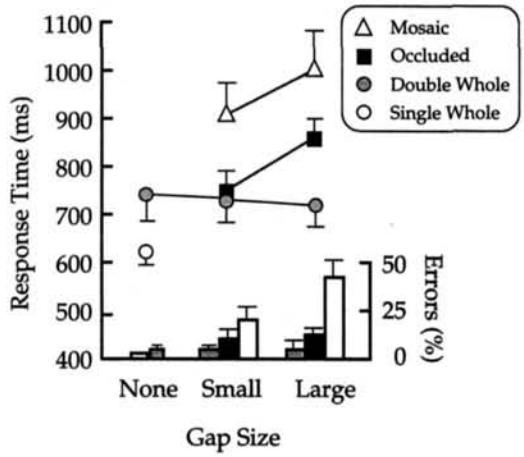


*Figure 2.* Mean correct response time and mean percentage of errors in Experiment 1. Bars represent standard errors of the mean in each condition. Note that only the double whole stimuli could be represented at all three levels of the gap size variable (none, small, and large).

saic, and occluded mosaic distractor). Follow-up and control analyses were based on the simple-effects procedure (Keppel, 1982) in which the mean square error and denominator degrees of freedom used in the $F$ ratio were taken from the highest-order interaction in the design. All $F$ values were compared with Huynh-Feldt epsilon-corrected $F$ values to detect departures from the ANOVA assumptions of "sphericity" and homogeneity of variance. No departures were detected in this experiment. In subsequent experiments, they were detected in only one instance, and in that case we reported the corrected probability value.

RT analyses revealed significant main effects of stimulus type, $F(3, 27) = 35.90$, $p < .01$, $MSE = 6{,}212.5$, and gap size, $F(1, 9) = 5.29$, $p < .05$, $MSE = 6{,}909.69$, as well as a significant interaction, $F(3, 27) = 10.89$, $p < .01$, $MSE = 2{,}486.68$. Analyses of the control displays revealed that RT to the single whole shapes was faster than to the double whole shapes, $t(27) = 6.10$, $p < .01$, which did not differ from whole shapes with either a small or large gap size, $t(27) < 1$. RT to the occluded mosaic distractors also did not differ from the small-gap-occluded shape regardless of whether the mosaic distractor had a small or a large gap, $t(27) < 1$, ruling out that RTs were affected by the presence or size of concavities in the shapes.

For the small gap size, responses to the occluded and whole shapes did not differ significantly, $t(27) < 1$, whereas those for the mosaic shapes were significantly slower than for the other two: occluded, $t(27) = 6.77$, $p < .01$; whole, $t(27) = 7.44$, $p < .01$. For the large gap size, responses to all three stimuli were significantly different, with the whole shape receiving the fastest responses, and were approximately equal to the small whole condition, $t(27) < 1$, followed by the occluded shapes, $t(27) = 5.87$, $p < .01$, and the mosaic shapes, $t(27) = 6.86$, $p < .01$.

The error analysis revealed significant main effects of gap size, $F(1, 9) = 6.28$, $p < .05$, $MSE = 113.47$, stimulus type, $F(3, 27) = 25.46$, $p < .01$, $MSE = 122.16$, and an interaction, $F(3, 27) = 4.39$, $p < .05$, $MSE = 96.76$. Errors followed the same pattern and direction as the RTs, although the only significant differences involved mosaic shapes, which were more error prone than other stimuli, $t(27) = 9.54$, $p < .01$, and significantly more error prone when gap size was large, $t(27) = 4.1$, $p < .01$.

### *Discussion*

These data point to an important limitation on the claim that shape completion is unmeasurably fast (Gerbino & Salmaso, 1987). As in the Gerbino and Salmaso study, we found that RTs to whole and occluded shapes were not statistically different for small amounts of occlusion. However, for larger amounts, RTs to occluded shapes were slower than for whole shapes, although still not as slow as for mosaic shapes. The error data showed that these conclusions were not contradicted by evidence of a speed–accuracy trade-off in any condition.

This result can be interpreted in two ways: First, it is possible that shape completion time was related directly to the amount of shape completed. However, it also is possible that there was a failure of the shape completion operation at the larger gap sizes and that observers were resorting to the more complex strategy enlisted in responding to mosaic shapes. To distinguish between these alternatives, we designed an experiment in which gap size could be varied more systematically. We also simplified the observer's task in an effort to reduce the number and complexity of the mental operations contributing to the RTs.

## Experiment 2

Observers were required to identify a single black item (the target shape) as either a circle or a square (two-alternative shape discrimination). The target appeared in one of five displays, as shown in Figure 3: whole, occluded, mosaic, whole mosaic distractor, and occluded mosaic distractor. Presented along with the target on most trials was a white shape (the distractor) that was either in front of (occluded) or behind (whole and mosaic) the target. The second important variable was gap size, which was initially tested in two phases. In Experiment 2A we sampled gap sizes between 3% and 45%; in Experiment 2B we examined gap sizes between 25% and 85%. We used the percentage of missing shape only as a convenient way to vary the spatial nature of the task. No theoretical implications were intended by this choice of metric, as opposed to, say, the number of missing pixels, or the percentage of missing contour.

One constraint this design placed on the appearance of the displays was that the occluded distractor in the mosaic display could not be overlapped much without protruding into the missing region of some mosaic targets. Our decision to permit only a small overlap therefore resulted in the visible portion of the distractor in the mosaic displays matching closely the visible portion of the distractor in the occluded displays. However, it also introduced a possible

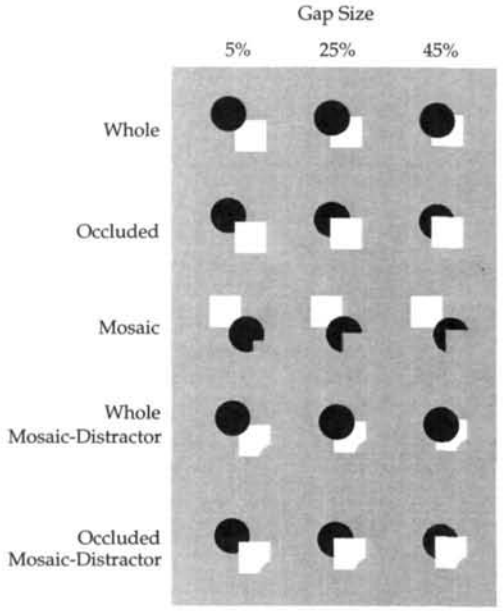


*Figure 3.* Examples of the displays used in Experiments 2–7. The target shape shown is a black circle; black squares were used equally often.

confound in the visible portion of the distractor in the whole displays (i.e., the size of the white region was similar in the occluded and mosaic shapes across gap size, but it decreased with gap size in whole shapes). We examined this by comparing RTs to the whole displays as a function of gap size.

## Method: Experiment 2A

*Observers.* Ten observers (6 women and 4 men, all of whom were right-handed) were recruited from the same subject pool as in the previous experiment.

*Stimuli and apparatus.* Each display was presented either 6° to the right or left of fixation on a gray background (50% of the pixels were white and 50% were black). The display could contain either a single black item or a black and a white item. Black items were defined as targets, white items as distractors. The items were circles (2.2°) and squares (2.0°), which were equated for total area.

The displays varied in stimulus type (whole, occluded, mosaic, occluded mosaic distractor, and whole mosaic distractor) and gap size (3%, 5%, 15%, 25%, and 45%). For the whole stimuli, no pixels were missing, so gap size was the percentage of pixels missing from the occluded distractor. There were three types of whole stimuli: single (one black target), double (one black target and one white distractor separated by 0.25°), and touch (one black target and one white distractor abutting one another). The black target item always appeared on the horizontal meridian. When a distractor was present, it appeared either above and to the right, or below and to the left, of the target. The side of presentation and distractor location were chosen randomly on each trial. For the mosaic stimuli, the distracting item was occluded by 5%.

*Procedure.* Each trial began with a fixation dot for 332 ms, which remained on during the display. The display then was presented for 200 ms, which was followed by a blank screen that remained blank until the observer responded (or 3 s had elapsed). There were 15 blocks of 60 trials. All other aspects were the same as in Experiment 1.

## Method: Experiment 2B

*Observers.* Ten observers (6 women and 4 men, all of whom were right-handed) were recruited from the same subject pool as in previous experiments.

*Stimuli, apparatus, and procedure.* The details of this experiment were the same as in Experiment 2A, except for gap size (now 25%, 50%, 70%, and 85%) and one replacement of stimulus type level: The occluded mosaic distractor stimulus was replaced with a mosaic-alone stimulus that was identical to the mosaic stimulus, except that no distractor item was present. Other minor changes included the removal of the fixation dot, the number of trials (now 20 blocks of 50 trials), and the positioning of the target item (it now appeared 0.5° above or below the horizontal meridian).

## Results: Experiment 2A

The mean correct RTs and the mean percentage of errors are shown in Figure 4A.[1] Not surprisingly, RTs to the single control are faster than to the double control, $t(144) = 2.58$, $p < .01$, and the double control was not different from the whole stimulus at the 3% gap size, $t(144) = 1.34$. Data from two other control conditions (i.e., occluded mosaic distractor and whole mosaic distractor) are not shown because they did not differ significantly from the corresponding experimental conditions. This indicates that the differences between occluded, whole, and mosaic shapes could not be attributed to the number of items that were incomplete in any given display.

There were significant main effects of stimulus type, $F(4, 36) = 13.42$, $p < .01$, $MSE = 946.53$; gap size, $F(4, 36) = 6.55$, $p < .01$, $MSE = 704.67$; and an interaction, $F(16, 144) = 4.12$, $p < .01$, $MSE = 496.62$. The RT function across gap size was different for each stimulus type. At the 3% gap size, response did not differ for any of the stimuli, largest $t(144) = 1.72$, whereas at the 5% level the only significant difference was between the mosaic and the whole stimulus, $t(144) = 2.40$, $p < .01$. At 15%, responses to the mosaic stimulus were significantly slower than to the occluded, $t(144) = 2.86$, $p < .01$, and whole, $t(144) = 4.35$, $p < .01$, stimuli, which did not differ from one other, $t(144) = 1.49$. At 25% and 45%, there were significant differences among all three stimuli, $ts(144) = 2.40–8.56$, $ps = .05–.01$. There was no gap size effect for whole stimuli ($p > .20$), suggesting that the size of the occluded distractor had little if any influence on RT. An analysis of

[1] The variability associated with each mean response time was summarized in two ways: standard deviations within observers (based on trial as the unit) and standard deviations between observers (based on observer as the unit). The mean within-observers standard deviations ranged from 102.5 to 171.8 and showed no systematic variation with stimulus condition. The between-observers standard deviations ranged from 52.6 to 79.2 and also showed no systematic variation. Correlations calculated between these two measures revealed no systematic relations.

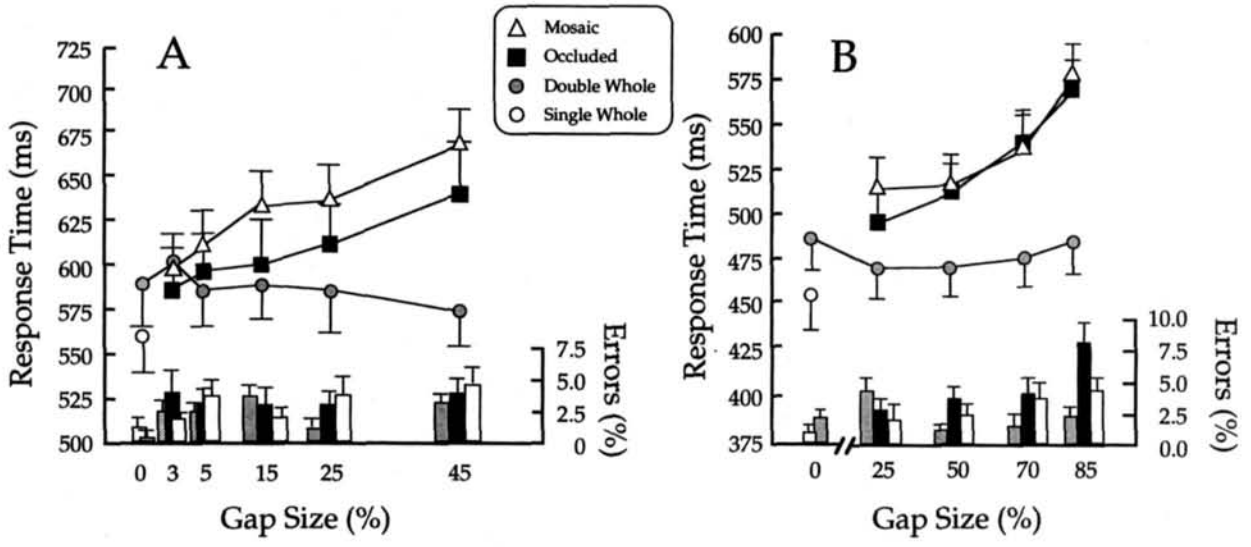


*Figure 4.* Mean correct response time and mean percentage errors in Experiment 2. A: Experiment 2A. B: Experiment 2B. Bars represent standard errors of the mean in each condition.

errors revealed no significant effects (*MSE*s = 6.94, 12.14, and 10.18 for stimulus type, gap size, and the interaction, respectively). Target shape (circle vs. square) did not show any significant effects, either main or in interaction, and are not mentioned in other experiments unless significant.

### *Results: Experiment 2B*

The mean correct RTs and the mean percentage of errors are shown in Figure 4B.[2] Once again, RTs to the single control were faster than to the double control, $t(108) = 8.04$, $p < .01$, and RTs for the double control were not different from the 25% whole, $t(108) = 1.74$, or 25% occluded stimulus, $t(108) = 1.56$. The whole mosaic distractor stimuli again did not differ in any way from the respective experimental condition. The mosaic-alone stimuli are not shown because they did not interact with the mosaic stimuli and simply showed an overall decrease in RTs that was not significantly different from that shown for the single versus the double control items.

There were significant main effects of stimulus type, $F(4, 36) = 36.55$, $p < .01$, $MSE = 951.2$; gap size, $F(3, 27) = 40.13$, $p < .01$, $MSE = 394.4$; and an interaction, $F(12, 108) = 6.49$, $p < .01$, $MSE = 295.50$. RTs to the occluded and mosaic stimuli were significantly slower than to the whole stimuli at all gap sizes, smallest $t(108) = 10.93$, $p < .01$. The only condition in which the occluded stimuli were significantly faster than the mosaic stimuli was at the 25% gap size, $t(108) = 2.38$, $p < .025$. Again, there was no gap size effect for whole stimuli ($p > .20$), suggesting that the size of the occluded distractor had little if any influence on RTs.

An analysis of errors revealed significant main effects of stimulus type, $F(3, 27) = 25.02$, $p < .01$, $MSE = 7.03$; gap size, $F(4, 36) = 11.51$, $p < .01$, $MSE = 8.04$; and an interaction, $F(12, 108) = 17.30$, $p < .01$, $MSE = 9.45$. The pattern and direction were similar to the RT data.

Finally, comparing across experiments, we noted an overall decrease in RTs from Experiment 2A to Experiment 2B. Possible reasons included the following: (a) There was a fixation point in Experiment 2A that remained on throughout the trial versus a blank screen of 1 s in Experiment 2B, between the termination of the feedback symbol and the onset of the display. This temporal gap between fixation and display might have permitted visual attention to switch more quickly at stimulus onset. (b) Observers generally made more errors in Experiment 2B, suggesting that they might have been trading accuracy for speed, relative to the group in Experiment 2A.

### *Discussion*

These data reveal two important characteristics about shape completion. First, responses to occluded shapes were not measurably different from whole shapes until the gap size exceeded 15%. However, from that point on, responses to occluded shapes became increasingly slower than those for whole shapes. This suggests that the completion operation is effectively instantaneous only for small amounts of occlusion. Second, at the largest gap sizes, there were essentially no differences between responses to occluded and mosaic shapes.

Thus, both of the alternatives entertained in the previous experiment appear to be true. Within a small range of gap sizes, shape completion operations are able to work rapidly

[2] Mean within-observers standard deviations ranged from 24.2 to 89.3. Between-observers standard deviations ranged from 53.9 to 87.8. Neither measure varied systematically with stimulus condition, and the two measures were not correlated with one another.

to supply a completed representation to later stages of visual processing. The small increases observed in the RTs also suggest that this primitive process requires more time for greater area. This alone could explain the different conclusions reached by Gerbino and Salmaso (1987), who tested a small gap size, and by Sekuler and Palmer (1992), who tested a larger gap size. Of course, there also are many other possibilities, including a differential sensitivity of the two methods to the temporal dynamics of completion and to the role of implicit memory in shape perception.

At the largest levels of occlusion, there appeared to be a failure of shape completion, at least in the operational sense that responses to occluded shapes did not differ from those to mosaic shapes, where phenomenal completion does not occur. However, this similarity is ambiguous. It merely could be reflecting the fact that completion now requires so much time that it takes as long as the more complex operations thought to be measured in responses to the mosaic shapes. However, it also could reflect a deeper similarity, such that the same complex operations may be involved in responding to both shape types. In the following experiments we attempted to dissociate these alternatives.

## Experiment 3

For this experiment we sought to influence shape completion differentially from the operations used to discriminate the mosaic shapes. Motion parallax is a powerful cue to depth (Eby & Loomis, 1993; Ono, Rogers, Ohmi, & Ono, 1988), so we used it to bolster the pictorial cues to depth in our displays (i.e., T-junctions). Three motion conditions were compared, as shown in Figure 5: target motion (i.e., the condition of interest); no motion (i.e., a replication of the previous experiment); and all motion (i.e., a control for the general effects of motion). In target motion, only the target moved back and forth, thereby revealing accretion and deletion of the distractor surface at the occlusion contour. In all motion, there was the same degree of motion for all items, but no item surfaces were accreted or deleted.

If the influence of motion parallax is different for occluded than mosaic shapes, it would suggest that the processing of occluded shapes was unique. In particular, motion parallax in the target-motion condition should benefit the completion operation for the occluded shapes. By contrast, the same degree of target motion should have no influence on the mosaic shape responses because motion would be unrelated to the perception of the shapes.

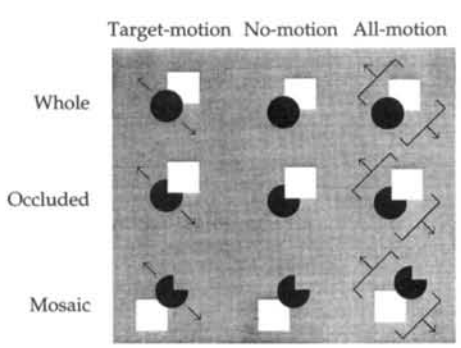


*Figure 5.* Examples of the displays used in Experiments 3 and 6. The target shape shown is a black circle; black squares were used equally often.

### Method

*Observers.* Ten students (5 women, 1 of whom was left-handed, and 5 men, 1 of whom was left-handed) were tested from the same subject pool as in the previous experiments.

*Stimuli, apparatus, and procedure.* Item motion was accomplished by repeating a display loop consisting of four 30-ms frames. The "moving" items were displaced by 2 pixels in both the horizontal and vertical directions from frame to frame. Thus, the same gap size was represented in each of the four frames of the motion sequence, although it was a slightly different portion of the shape in each frame. Seen as a sequence, the items oscillated at a rate of 2.8° per second and moved over a total distance of 0.2°. A trial sequence lasted 210 ms and consisted of the four frame sequences being presented twice. Two different mosaic stimuli were tested: one with accretion–deletion at the edges of the gap and one without. Other changes included the testing of double whole stimuli (items separated by 0.25°) in all three motion conditions. Testing consisted of 20 blocks of 50 trials.

### Results

The mean correct RTs and the mean percentage of errors are shown in Figure 6. The three double control stimuli (0% gap size) did not differ from each other, $F(2, 144) < 1$. An analysis of the two types of mosaic stimuli (i.e., with and without accretion–deletion at the edges of the gap) showed that there were no significant differences between them and so they were combined for all subsequent analyses.

There were significant main effects of stimulus type, $F(2, 18) = 46.24$, $p < .01$, $MSE = 754.94$; gap size, $F(4, 36) = 13.52$, $p < .01$, $MSE = 856.24$; and a Stimulus Type × Gap Size × Motion interaction, $F(16, 144) = 1.88$, $p < .05$, $MSE = 797.62$ (Huynh-Feldt epsilon-corrected $p < .08$). This interaction was examined further by testing the Gap Size × Motion interaction separately for each stimulus type. It was significant only for the occluded stimuli, $F(8, 144) = 2.51$, $p < .05$. Taking the difference in RTs between the 5% and 65% gap size as a summary measure, we found that this effect was largest for no-motion stimuli (mean RT difference = 82 ms), $t(144) = 6.47$, $p < .01$; smaller for the all-motion stimuli (mean RT difference = 51 ms), $t(144) = 4.00$, $p < .01$; and smallest for the target-motion stimuli (mean RT difference = 12 ms), $t(144) < 1$.

An analysis of errors revealed significant main effects of stimulus type, $F(4, 36) = 5.96$, $p < .025$, $MSE = 20.50$; gap size, $F(2, 18) = 3.08$, $p < .05$, $MSE = 14.68$; and a three-way interaction, $F(16, 144) = 1.74$, $p < .05$, $MSE = 18.38$. As in the RT data, the motion variable interacted with gap size only for the occluded stimuli, $F(8, 144) = 3.77$, $p < .01$, and the pattern and direction of effects was similar.

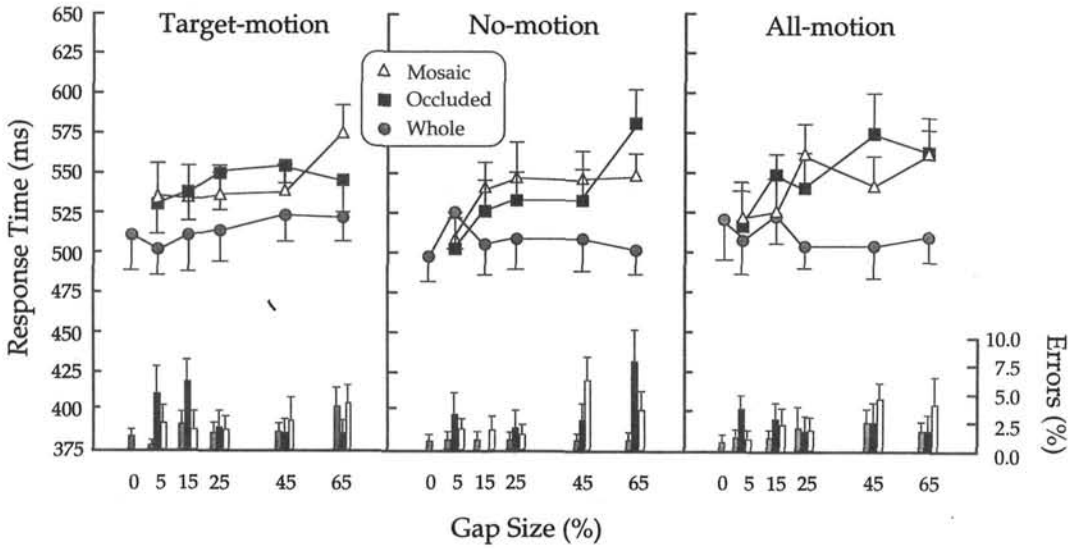


*Figure 6.* Mean correct response time and mean percentage of errors in Experiment 3. Bars represent standard errors of the mean in each condition.

### *Discussion*

The data in the no-motion and all-motion conditions confirmed the results of Experiment 2: that the gap size variable had a different effect on occluded and mosaic stimuli. In these conditions, responses to whole and occluded shapes were similar only for the smallest gap size. For the remaining gap sizes, increases in occlusion produced increasingly longer responses, to the extent that by the largest gap size, RTs to the occluded and mosaic shapes were essentially the same.

However, the most important result of this experiment concerned the influence of motion parallax on the occluded shapes. In the target-motion condition, RT increased slightly, but not significantly, with gap size. In the other two conditions, there was a much larger and significant rise in RTs with gap size. This suggested that time for completion was relatively independent of the size of the occluded area when completion was assisted by motion parallax.

This effect of motion parallax was not present in the mosaic stimuli. Here the increase in RTs with gap size did not vary as a function of the type of motion. This strongly suggests that the operations involved in completing an occluded shape are different from those involved in discriminating a mosaic shape, despite the fact that the total RT might have been similar in the two conditions.

We were surprised that there were no significant differences for the mosaic stimuli because there is some evidence that accretion–deletion information in itself may yield shape completion (Michotte et al., 1967). We therefore ran an additional experiment directly comparing mosaic stimuli with and without the accretion–deletion of edges at the borders of the missing portion. Although the subjective appearance of the stimuli was different in the two cases, there were no differences in RTs or errors. This points to an interesting discrepancy between reports of phenomenal appearance and measures of performance.

It also is noteworthy that this experiment might actually have underestimated the influence of motion parallax because observers were viewing the displays with both eyes. Bruno et al. (in press) pointed out that the effects of multiview contributions to depth (e.g., binocular parallax, motion parallax) may actually be suppressed by the other cues to a single image plane in shape completion experiments.

## Experiment 4

Thus far we have shown that shape completion in static pictorial displays seems to require more time as the area to be completed is increased. We have also suggested that discriminating occluded shapes involves different operations than discriminating mosaic shapes, even when the overall time for these discriminations may be similar. This was observed in the different pattern of RTs over gap size for occluded versus mosaic shapes and in the differential effects of motion parallax on the two shape types. In this experiment we examined the extent to which shape completion would be influenced by spatial attention.

Many theories of human vision are based on a distinction between two subsystems: (a) a rapid preattentive system that uses spatially parallel mechanisms, working in a bottom-up fashion, to register image features in independent topographic maps and (b) a later attentive system that takes advantage of flexible, but spatially serial, top-down processes to conjoin features from shared spatiotemporal locations (Posner, 1980; Treisman & Gelade, 1980; Treisman & Gormican, 1988; Zucker, 1987). One way to distinguish these subsystems operationally is through the visual search task, as mentioned in the introduction.

Another useful tool, and one better suited for our task, involves determining whether a given visual operation is influenced by the spatial orienting of attention (Posner, 1980; Posner & Dehaene, 1994; Posner & Petersen, 1990). Precuing the location of an impending target (a valid trial) facilitates many, but not all, subsequent tasks. For instance, simple feature discriminations based on color or form are largely unaffected by spatial precuing, suggesting that they are completed early, whereas more complex discriminations are affected, suggesting that they involve the more later attentional processes (Briand & Klein, 1987; Cheal, Lyon, & Hubbard, 1991; Prinzmetal, Presti, & Posner, 1986).

In this experiment we used an abrupt onset spatial cue. We anticipated that such cuing would influence all shape discriminations because a valid cue would be beneficial (and an invalid cue detrimental) to several of the visual operations required to make a discrimination response. However, the key question was whether cuing would influence the occluded shapes differently from the other shapes. If so, it would suggest that the completion operation was being influenced by the relatively later processes of spatial attention. Alternatively, if occluded shapes were not influenced uniquely, it would support the existence of an early (preattentive) shape completion operation.

## Method

*Observers.* Twenty-seven observers (20 women, 2 of whom were left-handed, and 7 men, 1 of whom was left-handed) were recruited from the same subject pool as in the previous experiments.

*Stimuli, apparatus, and procedure.* This experiment was identical to Experiment 2A, with three differences: the added variable of cue validity (valid, neutral, and invalid); the removal of several stimulus types (only whole, occluded, and mosaic were tested); and the selection of gap sizes (now 5%, 15%, 25%, 45%, and 65%).

Each trial began with a blank screen for 675 ms, followed by a fixation dot for 225 ms. An abrupt-onset stimulus cue (a 1.0° white square consisting of lines 0.25° wide) then was presented for 30 ms. After an additional 30 ms of blank screen, the target display was presented for 180 ms. The cue was presented in one of three locations: at the location of the impending target (valid), at the fixation point (neutral), or at the other potential target location (invalid). The relation between the cue and the target locations was random (unpredictable). Testing consisted of 12 blocks of 60 trials.

## Results

The mean correct RTs and the mean percentage of errors are shown in Figure 7. The three double control stimuli (0% gap size) differed significantly with cuing validity, $F(2, 416) = 3.64$, $p < .05$. Valid cues speeded the mean RTs compared with both neutral, $t(416) = 2.52$, $p < .01$, and invalid cues, $t(416) = 2.09$, $p < .05$, which did not differ from each other ($t < 1$). The control conditions did not differ from the whole stimuli at the 5% gap size for any level of cue validity ($t < 1$).

There were significant main effects of stimulus type, $F(2, 52) = 66.60$, $p < .01$, $MSE = 8{,}745.90$; gap size, $F(4, 104) = 74.59$, $p < .01$, $MSE = 1{,}945.71$; and validity, $F(2, 52) = 32.49$, $p < .01$, $MSE = 2{,}195.13$; and a Stimulus Type × Gap Size interaction, $F(8, 208) = 28.32$, $p < .01$, $MSE = 1{,}522.82$. A closer inspection showed that this interaction was significant even when each pair of gap size functions was tested separately: occluded versus mosaic, $F(4, 416) = 15.84$, $p < .01$; occluded versus whole, $F(4, 416) = 19.00$, $p < .01$; and whole versus mosaic, $F(4, 416) = 68.82$, $p < .01$. The Stimulus Type × Gap Size × Validity interaction was not significant, $F(16, 416) < 1$, $MSE = 1{,}248.39$.

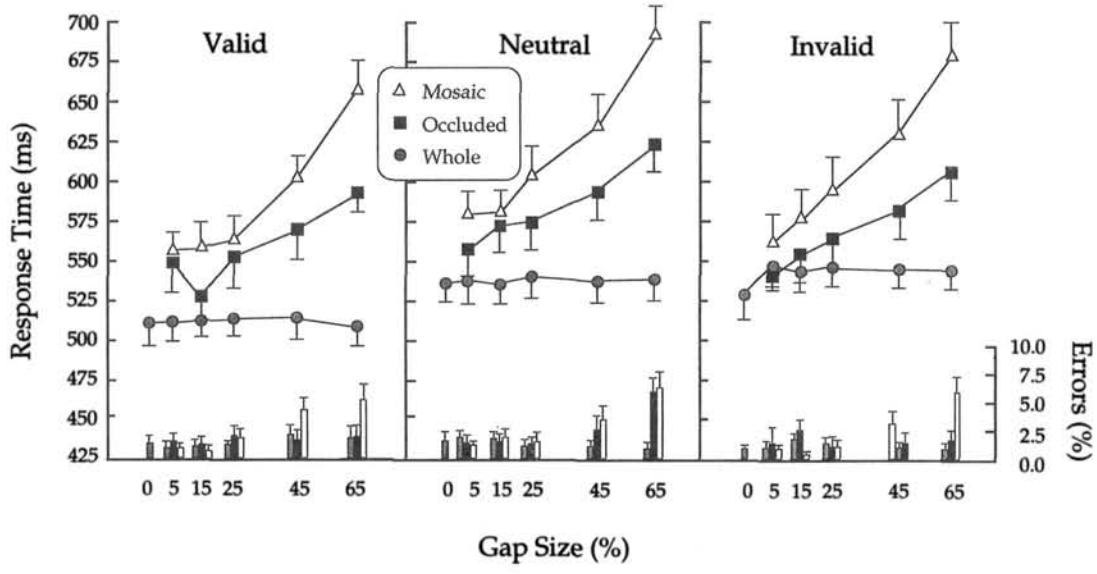


*Figure 7.* Mean correct response time and mean percentage of errors in Experiment 4. Bars represent standard errors of the mean in each condition.

An analysis of the error data yielded similar patterns and directions of effects. The effect of stimulus type was significant, $F(2, 52) = 8.26, p < .01, MSE = 24.21$, as was the effect of gap size, $F(2, 52) = 12.83, p < .01, MSE = 17.72$, and the interaction between the two, $F(8, 208) = 8.98, p < .01, MSE = 15.22$. The three-way interaction was again not significant, $F(16, 416) < 1, MSE = 14.36$.

### Discussion

The pattern of data for the three shape types again confirmed that different processes are involved in responding to occluded and mosaic shapes. As in the previous experiments, we found that there were no RT differences between the whole and occluded shapes for small gap sizes, pointing to a fast and efficient shape completion operation in this range. We also found a slowing of the responses to occluded shapes with increased gap size.

The effect of the spatial cue was strongly evident in all conditions, confirming that the cue we used was influential in this task. However, there was no evidence of a cuing effect that was unique to the occluded shapes. This suggests that shape completion in our shape discrimination task is an early visual operation. This conclusion is consistent with that of other researchers who have studied completion in more complex visual displays using visual search (Rensink & Enns, in press) and texture segmentation tasks (He & Nakayama, 1992).

## Experiment 5

In the next set of experiments (Experiments 5–7), observers responded to the shape of the visible portion of the target rather than to its interpolated shape. This forces them to adopt a "proximal" rather than the preferred "constancy" mode of perception (Rock, 1983). Thus far, we have argued that the process is primitive because it appears to operate quickly and is uninfluenced by manipulations of spatial attention. An additional important criterion of any operation of early vision is its immunity to influence from higher level goals (Enns & Rensink, 1991; Rensink & Enns, 1995; Zucker, 1987). Therefore, we examined the *perceptual intrusion* caused by the involuntary completion of the stimulus shape on the observer's task to respond only to the shape of the visible portion.

The design of Experiment 5 mirrored that of Experiment 2, except that observers were asked to indicate whether the black item (the target shape) was a complete or an incomplete shape (a two-alternative shape discrimination). Whole shapes received one response, whereas occluded and mosaic shapes received the other.

### Method

*Observers.* Ten observers (6 women and 4 men, all of whom were right-handed) were recruited from the same subject pool as in the previous experiments.

*Stimuli and procedure.* Aside from the change in task, this experiment followed Experiment 2A. The conditions tested included stimulus type (whole, occluded, mosaic, occluded mosaic distractor, and whole mosaic distractor) and gap size (5%, 15%, 25%, 36%, and 54%), along with two control stimuli (whole single and whole double, in which the two items were separated by 0.25°). Testing consisted of 15 blocks of 60 trials.

### Results

The mean correct RTs and the mean percentage of errors are shown in Figure 8.[3] RTs to the double control stimulus were significantly slower than to the single control stimulus, $t(144) = 2.97, p < .01$, but not different from the whole stimulus at the 5% gap size, $t(144) = 1.61$. Responses to each of the mosaic distractor control stimuli were not significantly different from the corresponding experimental stimuli, so we did not analyze them further. As mentioned previously, these conditions were included to test whether differences between the mosaic and occluded stimuli were related simply to the presence of deep concavities in the displays. This hypothesis was not supported.

Because the observer's response to the whole stimuli was different from that to the occluded and mosaic stimuli, we were cautious in comparing across these conditions. We first conducted all analyses excluding the whole condition and then repeated the analyses including it. This yielded no significant differences in this or any subsequent experiments, so we report the full analyses.

There were significant main effects of target shape, $F(1, 9) = 9.30, p < .05, MSE = 2{,}030.24$; stimulus type, $F(4, 36) = 6.39, p < .01, MSE = 4{,}377.82$; gap size, $F(4, 36) = 36.64, p < .01, MSE = 875.04$; and an interaction, $F(16, 144) = 5.61, p < .01, MSE = 874.76$. The shape effect reflected generally smaller RTs to squares than circles (12 ms), but, because it did not interact with any other variable, we do not discuss it further.

RTs to the occluded shapes were significantly slower than to the mosaic shapes for all levels of occlusion except the largest: 5%, $t(144) = 6.48$; 13%, $t(144) = 4.09$; 25%, $t(144) = 3.70$; 36%, $t(144) = 2.72$; 54%, $t(144) = 1.53$, all $ps < .01$. RTs to the occluded shapes were significantly slower than to the whole shapes for the first three gap sizes—5%, $t(144) = 8.24$; 13%, $t(144) = 3.39$; 25%, $t(144) = 3.51$, all $ps < .01$—but not for the larger gap sizes—36%, $t(144) = 1.08$; 54%, $t(144) < 1$. Responses to the whole and mosaic shapes did not differ from each other at any gap size, $ts(144) < 1$ for all levels.

An error analysis revealed significant main effects of stimulus type, $F(4, 36) = 5.96, p < .01, MSE = 18.30$; gap size, $F(4, 36) = 9.72, p < .01, MSE = 14.63$; and an interaction, $F(16, 144) = 4.73, p < .01, MSE = 10.46$. The interaction was attributable solely to the high error rate for

[3] Mean within-observers standard deviations ranged from 32.1 to 96.7. Between-observers standard deviations ranged from 96.6 to 149.2. Neither measure varied systematically with stimulus condition, and the two measures were not correlated with one another.

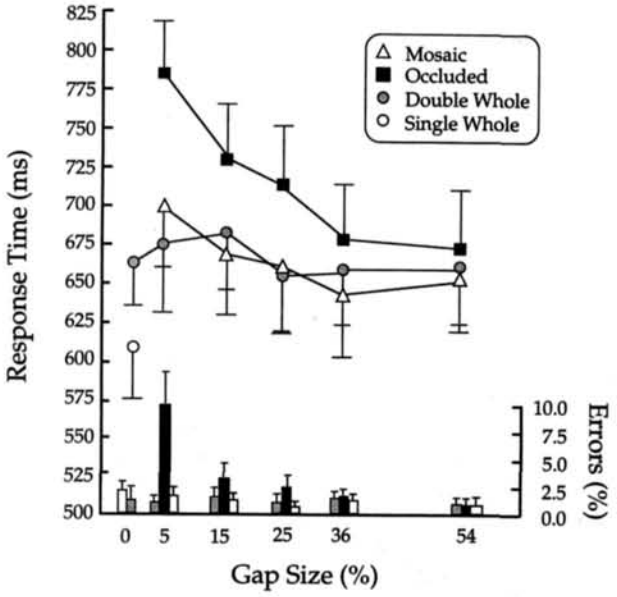


*Figure 8.* Mean correct response time and mean percentage of errors in Experiment 5. Bars represent standard errors of the mean in each condition.

the occluded stimuli at the 5% gap size. Otherwise, the pattern and direction of effects were similar to the RT data.

### *Discussion*

These data confirm that shape completion is an obligatory process. This could be seen in the generally slower and less accurate responses to occluded versus whole or mosaic shapes. Second, the strength of the intrusion caused by this process diminished as the size of the occluded area was increased. Whereas responses to whole and mosaic shapes varied little with gap size, and did not differ reliably from one another, responses to occluded shapes were much slower at small gap sizes, decreasing gradually in difficulty with gap size and becoming essentially the same as responses to the other shape types at the largest gap size.

This pattern of results is consistent with a primitive shape completion process, which takes more time because of the greater area. For small gap sizes, completion is rapid and thus a hindrance to the demands of the visible shape task. As gap size increases, shape completion presumably takes more time and thus the observer may be able to respond to the shape of the visible portion before a completed representation of the occluded shape can interfere. Whether shape completion is unfinished because there is not enough time for the process, or because there is insufficient visible shape for the process to execute, cannot be determined here. In any case, the unique effect of gap size on the occluded shapes in this task is another piece of converging evidence that the processes involved in discriminating mosaic shapes are much different from those involved in discriminating the visible portions of occluded shapes.

## Experiment 6

To confirm that the effects of gap size on occluded shapes were depth related (i.e., one shape occluding another in a different depth plane), we used the motion parallax manipulation used in Experiment 3. As in that experiment, we expected motion parallax cues in the target shape to improve the efficiency of the completion process. However, because the observer's task was now to report on the shape of the visible portion of a target, we expected motion parallax to interfere with performance rather than to facilitate it.

### *Method*

*Observers.* Twelve observer (9 women and 3 men, all right-handed) were recruited from the same subject pool as before.

*Stimuli and procedure.* This experiment was essentially the same as Experiment 3, except that observers performed the visible shape task. The three variables that were varied were stimulus type (whole, occluded, mosaic, occluded mosaic distractor, and whole mosaic distractor), gap size (5%, 20%, 30%, 40%, and 55%), and motion type (no motion, all move, and target move). Testing consisted of 20 blocks of 50 trials.

### *Results*

The mean correct RTs and the mean percentage of errors are shown in Figure 9. Responses to the double control stimuli did not vary as a result of the motion manipulation ($F < 1$), and there were no differences found between the mosaic distractor controls and the corresponding experimental stimuli.

There were significant main effects of stimulus type, $F(4, 44) = 5.13$, $p < .01$, $MSE = 9{,}313.85$; gap size, $F(4, 44) = 47.11$, $p < .01$, $MSE = 1{,}317.10$. The main effect of motion was not significant, $F(2, 22) = 0.05$, $MSE = 730.60$. These effects were moderated by two higher order interactions: Stimulus Type × Gap Size, $F(16, 176) = 7.28$, $p < .01$, $MSE = 924.19$, and Stimulus Type × Motion, $F(8, 88) = 2.37$, $p < .05$, $MSE = 909.35$. The Motion × Stimulus Type × Gap Size interaction was not significant, $F(32, 352) = 1.13$, $MSE = 824.78$.

The Stimulus Type × Gap Size interaction, as in the previous two experiments, reflected the specific sensitivity of the occluded stimuli to the small gap sizes. Pairwise comparisons of the functions revealed that the occluded function was influenced more by gap size than the function for whole, $F(4, 352) = 15.05$, $p < .01$, and mosaic, $F(4, 352) = 5.78$, $p < .01$, which were themselves different from each other, $F(4, 352) = 2.43$, $p < .05$.

The Stimulus Type × Motion interaction reflected the differential influence of the target-motion condition on occluded versus whole shapes, $F(2, 88) = 3.36$, $p < .05$. Whereas for whole shapes this condition yielded the fastest RTs (mean RTs = 517, 528, and 523 ms for target motion, no motion, and all motion, respectively), it was the slowest condition for the occluded shapes (mean RTs = 553, 541, and 545 ms for target motion, no motion, and all motion,

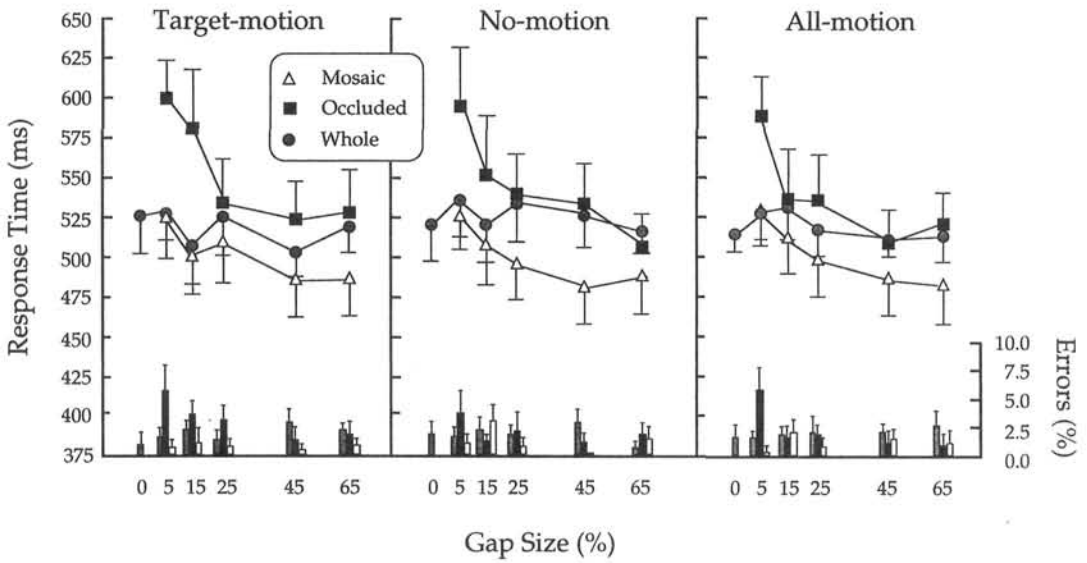


*Figure 9.* Mean correct response time and mean percentage of errors in Experiment 6. Bars represent standard errors of the mean in each condition.

respectively). This effect was most pronounced in the 20% gap condition. Here target-motion/occluded RTs were 27 ms slower than no-motion/occluded RTs, $t(352) = 2.28$, $p < .05$, and 40 ms slower than all-motion/occluded RTs, $t(352) = 3.34$, $p < .01$. By contrast, target-motion/whole RTs were 12 ms faster than no-motion/whole RTs, $t(352) = 1.03$, $p > .05$, and 26 ms faster than all-motion/whole RTs, $t(352) = 2.22$, $p < .05$.

An analysis of errors revealed significant main effects of stimulus type, $F(4, 48) = 3.82$, $p < .01$, $MSE = 15.93$; gap size, $F(4, 48) = 4.53$, $p < .01$, $MSE = 12.46$; and the interaction, $F(16, 176) = 2.89$, $p < .01$, $MSE = 9.64$. In general, the errors followed the same pattern and direction as the RTs.

### *Discussion*

The data confirmed that the effect of gap size on RTs to the occluded shapes was depth related. That is, when motion parallax was used to strengthen the interpretation of a target shape occluded by a nearer shape, there was an increase in response interference. This increase was the most pronounced in the 20% gap size condition. One reason that the small-to-intermediate gap sizes may be the most vulnerable to the effects of motion parallax is that the completion process may have finished quickly in the smallest gap sizes solely because of the pictorial cues (i.e., T-junctions). Conversely, this process may take so long at the largest gap sizes that even the benefits of additional depth cues do not permit it to be finished before a response can be made of the visible portion. This leaves the intermediate gap sizes to be most readily influenced by additional support for the interpretation of shape occlusion.

We caution again that the effects of motion parallax might have been weakened by binocular viewing in this experiment (Bruno et al., in press). As in Experiment 3, we also noted that the accretion–deletion information in the mosaic condition contributed to the appearance of a subjective occluder, although its presence did not seem to have any influence on performance.

## Experiment 7

Responding to the visible portion of an occluded shape is an attention-demanding task, as shown by the intruding influence of the completed shape in the previous two experiments. Therefore, we would expect the spatial cuing of attention to influence responses to the occluded shapes in this task, possibly even with a different effect for small and large gap sizes.

There are two different ways in which this influence on the gap size effect might be felt. One would be for valid spatial cues to short-circuit the normal completion process, thereby providing attentional access to the visible portion of occluded shapes more readily on valid than on invalid trials. This would constitute a top-down influence (i.e., an interruption) on the lower level completion operation. Furthermore, it would predict an interaction between cue validity and gap size for occluded shapes because the valid occluded shapes should be responded to in the same way as mosaic shapes (i.e., with a much smaller gap size effect).

A second way would be for valid spatial cuing to speed up access to the visible portion of shapes that have not yet been completed. That is, spatial cuing should have little effect on occluded shapes with small gap sizes because shape completion occurs for them quickly and with no regard for the locus of attention (as shown in Experiment 4). However, for larger gap sizes, a "horse race" might ensue between the completion process and attentional access to the uncompleted visible portion. Spatial cuing then would be expected

to influence responses to the shapes with larger gap sizes, just as it should for all mosaic shapes.

## Method

*Observers.* Twenty-four observers (14 women, 1 of whom was left-handed, and 10 men, 1 of whom was left-handed) were recruited from the same subject pool as before.

*Stimuli and procedure.* Aside from the task given to observers (indicate whether the black item is complete or incomplete), this experiment was identical to Experiment 4. The three variables manipulated were stimulus type (whole, occluded, and mosaic), gap size (5%, 15%, 25%, 45%, and 65%) and cue validity (valid, invalid, and neutral). Testing consisted of 12 blocks of 60 trials.

## Results

The mean RTs and the mean percentage of errors are shown in Figure 10. Cue validity, although in the predicted direction, had no significant effect on the control stimuli (0% gap size in the whole condition), $F(2, 368) = 1.23$.

There were significant main effects of stimulus type, $F(2, 46) = 50.22$, $p < .01$, $MSE = 7{,}393.50$; gap size, $F(4, 92) = 50.13$, $p < .01$, $MSE = 2{,}299.96$; and validity, $F(2, 46) = 30.92$, $p < .01$, $MSE = 2{,}175.14$. These were moderated by three higher order interactions: Stimulus Type × Gap Size, $F(8, 184) = 12.84$, $p < .01$, $MSE = 1{,}992.23$; Stimulus Type × Validity, $F(4, 92) = 4.17$, $p < .01$, $MSE = 1{,}701.25$; and Stimulus Type × Gap Size × Validity, $F(16, 368) = 1.68$, $p < .05$, $MSE = 1{,}348.80$.

Closer inspection of the Stimulus Type × Gap Size interaction revealed that responses to the three shape types had much different patterns across gap size. All paired comparisons of the three types revealed significant two-way interactions: occluded versus whole, $F(4, 368) = 34.68$, $p < .01$; occluded versus mosaic, $F(4, 368) = 18.62$, $p < .01$; and whole versus mosaic, $F(4, 368) = 3.61$, $p < .01$. Again, this demonstrated that the occluded stimuli were especially sensitive to small gap sizes, consistent with the notion that an involuntary completion process was slowing responses to the stimuli.

The effects of cue validity were examined more closely by first retesting the three-way interaction with the neutral cuing condition removed. This interaction was significant, $F(8, 192) = 2.05$, $p < .05$. To explore it, we tested the standard orienting effect (invalid RT − valid RT) for each stimulus type. This measure was significantly different from zero for each stimulus: mean difference for whole = 38 ms, $t(192) = 8.07$, $p < .01$; occluded = 25 ms, $t(192) = 3.88$, $p < .01$; and mosaic = 18 ms, $t(192) = 3.70$, $p < .05$. It was larger for whole than for occluded, $F(1, 192) = 5.91$, $p < .05$, and it did not differ for occluded and mosaic, $F(1, 192) = 1.26$. The effect of gap size on the orienting measure also varied with stimulus type: It decreased with gap size for whole stimuli, linear $F(1, 192) = 5.91$, $p < .05$; it increased with gap size for occluded stimuli, linear $F(1, 192) = 4.48$, $p < .05$; and it was generally constant for mosaic stimuli, linear $F(1, 192) < 1$.

An analysis of errors revealed main effects of stimulus type, $F(2, 46) = 21.92$, $p < .01$, $MSE = 40.04$; gap size, $F(4, 92) = 11.60$, $p < .01$, $MSE = 24.34$; and the interaction, $F(8, 184) = 11.47$, $p < .01$, $MSE = 24.85$. The interaction reflected the high error rates for the occluded stimuli in the small gap size conditions. For the 5% and 15% gap sizes, the occluded stimuli were more error prone than both the whole stimuli—5%, $t(386) = 6.39$, $p < .01$; 15%, $t(386) = 1.88$, $p < .05$—and the mosaic stimuli—5%, $t(386) = 10.26$, $p < .01$; 15%, $t(386) = 3.61$, $p < .01$.

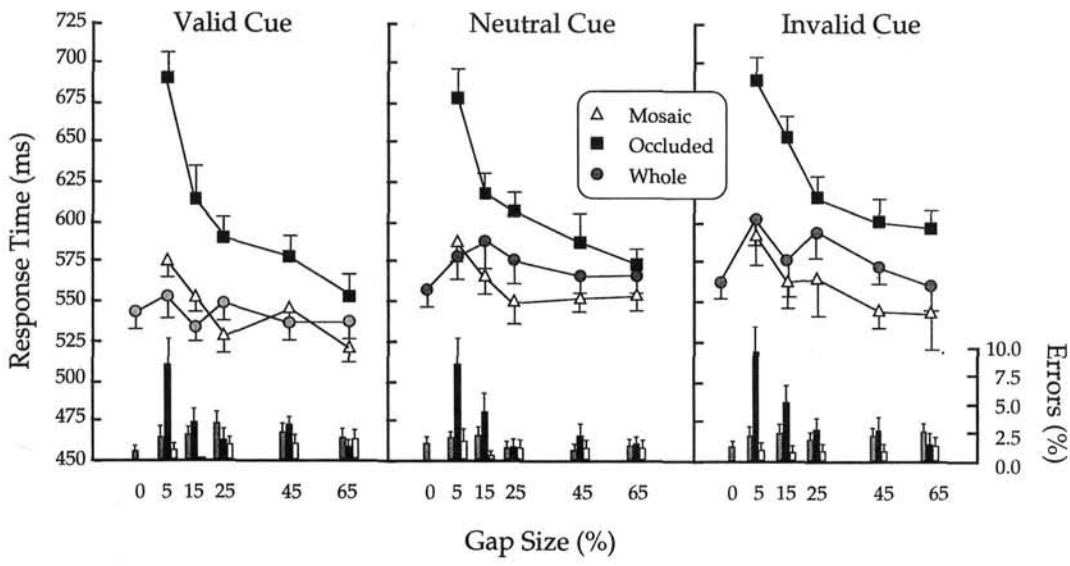


*Figure 10.* Mean correct response time and mean percentage of errors in Experiment 7. Bars represent standard errors of the mean in each condition.

Otherwise, the pattern and direction of effects were similar to the RT data.

### *Discussion*

These data revealed an interaction between spatial cuing and gap size. Whereas the effect of cuing was roughly constant across gap size for mosaic shapes, there was a systematic increase in the cuing effect with gap size for occluded shapes. This is consistent with attention having its strongest influence on shapes that have not yet been completed, thereby confirming once again the preattentive and primitive nature of shape completion.

Interestingly, for whole shapes, the cuing effect decreased with gap size. We think this might reflect a decreasing interference effect from the occluded distractor. Note that as gap size increased, the amount of the distractor that was visible behind the target decreased. Although this did not seem to affect RTs in the previous experiments, in this experiment they were showing up in the spatial orienting effect. This is consistent with other evidence that distractor effects are larger when the target location has been miscued (Akhtar & Enns, 1989).

Finally, these data again replicated the general finding that occluded mosaic and occluded shapes are processed in different ways, as shown by the different baseline pattern of responses across gap size.

## General Discussion

In this research the completion of occluded shapes was shown to be a primitive perceptual process in three different ways. First, it occurred rapidly, at least rapidly enough to facilitate the task of discriminating the interpolated shape of a briefly presented simple target and rapidly enough to interfere with the task of discriminating the visible portion of the same briefly presented target. Inspection of the stimuli used in these experiments (see Figures 1, 3, and 5) shows that, strictly speaking, none of the tasks required a completion process of any kind. There was sufficient information in each of the stimuli to permit an accurate discrimination between circle and square (Experiments 2–4) and between complete and incomplete (Experiments 5–7). Nonetheless, the data were consistent with the existence of a rapid shape completion process. This was evident in the generally more rapid RTs to occluded shapes than mosaic shapes in a task requiring a "constancy" mode of perception (Experiments 2–4) and in the much slower RTs to occluded than mosaic shapes in a task requiring a "proximal" mode (Experiments 5–7).

Second, shape completion was not influenced by a manipulation of spatial attention, despite this variable influencing other cognitive components in the tasks. In Experiment 4, spatial cuing decreased RTs to targets in validly cued locations and increased RTs to targets in invalidly cued locations. Yet, this manipulation had no differential effect on discriminations of occluded versus mosaic shapes or on the associated gap size effect. In Experiment 7, in which observers were forced to adopt a proximal mode of perception, spatial attention did influence responses to some occluded shapes. Specifically, valid spatial cuing was more beneficial for discriminating shapes with large amounts of occlusion (i.e., shapes that presumably had not yet been completed or were more difficult to complete). This confirms that (a) shape completion of small occluded regions is a primitive visual operation in the sense of lying outside the influence of top-down attentional mechanisms and (b) when shape completion is made more time-consuming or difficult because of a larger hidden region, spatial attention can be seen to exert an influence.

Third, shape completion intruded involuntarily into a task in which observers were asked to discriminate the shape of the visible portion of a target shape. Although the visible portion of the target shape was identical in the mosaic and occluded stimuli, observers took much longer to make this discrimination for occluded shapes. Furthermore, this difference diminished as the size of the hidden portion was increased, such that at the largest gap sizes tested, responses to mosaic and occluded shapes were no longer different. This bears a resemble to the classic Stroop (1935) task (see the review by MacLeod, 1991), in which a highly automated procedure (reading printed text) is placed in conflict with the observer's primary task (naming the ink color of the words). However, given the data for mice (Kanizsa et al., 1993), newborn chicks (Regolin & Vallortigara, 1995), and human infants (Kellman & Spelke, 1983), the automated nature of the shape completion process probably is the consequence of innate neural circuitry rather than of overlearning, as it is in the Stroop paradigm. The obligatory nature of shape completion, at least for the smaller gap sizes, thus confirms that proximal shapes are much more difficult for observers to access than the completed "constancy" shapes (He & Nakayama, 1992; Rensink & Enns, 1995).

The most important result of this research must be interpreted in the context of the aforementioned three findings. It is that the time required for shape completion was measurably related to the size of the area completed, despite the otherwise primitive nature of the operations involved. This was demonstrated in each of seven experiments by RTs that varied systematically with the size of the occluded portion of a shape. This interpretation hinges, of course, on the different RT functions over gap size for occluded and mosaic shapes. Despite their similarity in retinal stimulation, RTs rose more rapidly with gap size for occluded shapes in the completed shape task (Experiments 2–4) and declined more precipitously with gap size in the visible shape task (Experiments 5–7).

The use of motion parallax as an additional depth cue in Experiments 3 and 6 provided additional evidence that different processes were responsible for the responses to occluded and mosaic shapes. In particular, motion parallax that was consistent with the pictorial cues to occlusion (i.e., T-junctions) worked to facilitate the completion of the target shape. It therefore decreased the gap size effect for occluded shapes in the constancy mode task (Experiment 3) because it made it easier for observers to complete the

shapes. On the other hand, motion parallax increased the gap size effect for occluded shapes in the proximal mode task (Experiment 6) because it made it even more difficult for observers to access the retinal shape. This result goes beyond merely pointing to different processes involved in the two shape types. It also shows that the processing of occluded shapes was related to their interpretation as objects in 3-D space. This strategy is reminiscent of that used by He and Nakayama (1992), who used stereoscopic depth to confirm that interpretations based on the pictorial cues of T-junctions were related to the hypothetical construct of shape completion.

## *Theoretical Implications*

What are the implications of these findings for theories of vision generally and for theories of shape completion more specifically? We examine several different theories in turn. In each case, we briefly summarize the theory with respect to our data before discussing the implications of our results for the theory. An outline of this discussion is given in Table 1.

*Early versus later stages of vision.* Many theories divide visual processes into two fundamentally different classes. *Early vision* corresponds to operations that are carried out in parallel over space, within a few hundred milliseconds, and without influence from higher level goals (e.g., Helmholtz, 1909/1962; Treisman, 1991; Wolfe, 1994; Zucker, 1987). The *later visual processes*, by contrast, are spatially serial, slower, and guided by cognitive strategies. The early stage is thought to extract simple "features" from the image, registering them in independent topographic maps, whereas the later stage assembles these features into coherent descriptions of the external world. However, recent reports

Table 1
*Positive and Negative Implications of Our Data for Various Theories*

| Theory | Relevant claims | Positive implications | Negative implications |
|---|---|---|---|
| Two-stage theories (Treisman, 1991; Zucker, 1987) | Early parallel stage of image-based features followed by a later serial stage of scene-based features | None | Early stage contains scene-based information regarding completed objects<br>It is possible to measure the time course of an early-stage process |
| Introspection and gestalt (Kanizsa & Gerbino, 1982; Koffka, 1935) | Perception governed by the minimum principle (the simpler of two possible shapes is the one perceived) | Completed shapes are "simpler" in that they are processed faster and more accurately | Time for shape completion increases with the size of the occluded region |
| | Shape completion is accomplished by primary processes (seeing), not by secondary processes (thinking) | Shape completion is a primitive process in that it is rapid, unaffected by attention, and obligatory | |
| Coding theory (Buffart, Leeuwenberg, & Restle, 1981) | Shape complexity is quantified by applying recursive grammatical rules to image elements<br>Completed shapes are simpler than mosaic shapes | The completed shape, not the mosaic shape, tends to predict performance | There is no account of the gap size effects in current versions of coding theory |
| Relatability theory (Kellman & Shipley, 1991) | Shape completion occurs when extrapolated surface edges meet at angles greater than 90°<br>Shape completion deteriorates with increases in extrapolated distance | Gap size effect is consistent with both angle and distance limitations | There is no evidence for angle size limitations in the current data |
| Hybrid theories (Boselie, 1988; Wouterlood & Boselie, 1992) | Both global simplicity (coding theory) and local simplicity (relatability theory) are taken into account | Implications from both previous theories apply | Implications from both previous theories apply |
| Form and color and depth (FACADE) (Grossberg, 1987, 1994) | Completion of disjoint colinear edges is accomplished by iterative and cooperative processes that propagate edge and surface information | Completion time increases with gap size | Can noncolinear edges be completed by this model? |

(Aks & Enns, 1992; Enns & Rensink, 1991; He & Nakayama, 1992; Kleffner & Ramachandran, 1992; Rensink & Enns, 1995) have forced theorists to take into account that the early stage is sensitive to complex scene-based properties such as the direction of lighting, 3-D orientation, texture gradients, element grouping, and object occlusion (Treisman & Sato, 1990; Wolfe, 1994). The net effect of these reports has been to weaken the traditional dichotomy between early versus late processes.

From this perspective, one contribution of the current research is to show that some aspects of shape completion are indeed primitive, even when measured by methods other than the visual search and texture segmentation tasks that are popular with vision researchers. In particular, the independence of completion on manipulations of spatial attention, and its strong tendency to intrude on an otherwise simple visual discrimination, provide converging evidence that shape completion is indeed primitive.

A second contribution is the finding that, despite the primitive nature of completion, its operation takes measurable time and this time is related to the size of the spatial region that has been occluded. This points to the importance of establishing methods that probe the workings of so-called early vision in greater detail. Traditionally, researchers have used behavioral methods with dichotomous outcomes to study the early versus late vision dichotomy (e.g., pop-out vs. serial visual search functions; effortless vs. effortful texture segmentation). Methods using parametric variation of stimulus factors, such as those used here, and those used by Rensink and Enns (1995), show that there is much more structure (and complexity) beneath the surface of early visual processes than has been appreciated previously.

*Introspection and gestalt theory.* The perceptual completion of occluded shapes has been seen most often as a manifestation of the gestalt principle of *Pragnanz* (i.e., the minimum principle). That is, the preferred perceptual interpretation of an ambiguous display is the one that is the most parsimonious (Koffka, 1935). For example, if the visual system is forced to choose between a more complex 2-D description (i.e., a contiguous irregular shape) and a simpler 3-D description (i.e., a partially occluded regular shape), it opts for the 3-D version (Dinnerstein & Wertheimer, 1957; Hochberg & Brooks, 1960).

Note that the phenomenological theories also often propose two distinct stages of visual processing. For example, Kanizsa and Gerbino (1982) distinguished between the *primary processes* of "seeing," which are responsible for grouping retinal features into larger wholes through the laws of organization (e.g., proximity, similarity, good continuation), and the *secondary processes* of "thinking," such as the identification and categorization of these larger wholes as meaningful objects. According to this account, shape completion is a manifestation of the primary processes, particularly the law of good continuation. This view is defended by appeal to the observations that partly occluded shapes rarely appear to be fragmented, that prior knowledge does little to alter the appearance of an occluded shape, and that the completed shape appears to be available instantaneously in consciousness.

Our results thus can be seen as confirmation, both that shape completion serves to simplify the interpretation of stimulus shapes (i.e., responses were faster in Experiments 1–4 and slower in Experiments 5–7 for occluded shapes than mosaic shapes even though they were retinally identical) and that shape completion is a primary process (i.e., responses differed to occluded and mosaic shapes even though the identification and categorization aspects of the response were identical).

However, the results also demonstrate an important aspect of perceptual processing that appears to be inaccessible to introspection: that the time required for completion is related to the size of the occluded region. This points to limits on what can be learned through introspection and, if nothing else, should encourage others to test their hypotheses using performance measures.

*Coding theory.* The most fully developed effort to formalize the gestalt concepts, and to apply them to the appearance of occluded shapes, is that of coding theory (Buffart, Leeuwenberg, & Restle, 1981). The essential concept of this theory lies in the relative complexity of various alternative "codings" of a given stimulus. To begin, every line segment (or edge) and angle in a stimulus is labeled. Simplifying rules then are applied to take advantage of redundancies such as symmetry, repetition, and rotation in the stimulus. Each possible code is assigned a complexity score, and the code with the smallest score is predicted to be the one perceived. Not surprisingly, the theory predicts that a display of partly occluded shapes will generate a code with a smaller score for the occlusion interpretation than the mosaic interpretation.

Our results are certainly in broad agreement with this theory because the data show that responses to an occluded shape usually are governed by the occlusion interpretation. However, our results also reveal something in their details that is not predicted: the variable of gap size. As currently stated, coding theory predicts that the occlusion interpretation is equivalently simpler than the mosaic interpretation at all levels of gap size. This is because the shapes contain the same number of line segments and the same degree of symmetry at all levels of gap sizes and the theory makes no provision for element length or size.

It is conceivable that coding theory could be modified to incorporate element size or length into its considerations. However, this would have to be done carefully because, depending on the assumptions made, such changes could lead either to an increase or a decrease in complexity with gap size. For example, if the length of edge segments factored into the code, the complexity of the circle would increase with increasing gap size because the total perimeter of that shape increases with gap size. On the other hand, if visible surface area were taken into account, the code would decrease because this measure decreases with gap size. Therefore, the only strong conclusion that can be made at present is that there is clearly something more to shape completion than the calculation of a complexity code for the stimulus display as a whole.

*Relatability theory.* At the opposite end of the spectrum from theories based on global display simplicity are those

that are based on local feature considerations. The most fully developed is *relatability theory* (Kellman & Shipley, 1991; Shipley & Kellman, 1992a), which is a formalization of the gestalt principle of good continuation for subjective contours and for shapes that are partly occluded. The theory proposes that the visual system will connect two noncontiguous edges that are relatable as part of a more general unit formation process. Relatable edges are those with extensions meeting at angles between 90° and 180°. The authors reported that the likelihood of "seeing" a completed figure increases systematically with the size of the angle that must be interpolated, with the 50% threshold occurring at around 90°. Their data also reveal something that their theory does not explicitly predict: a systematic relation between size of the gap to be bridged and the subjective clarity of the completed figure, with clarity decreasing as a function of the ratio of the gap to the entire edge.

Our findings thus are relevant to several of the issues addressed by this theory. First, the finding that time for completion increased with gap size is consistent with both the angle size and the gap size limitations. As more of the circle target shape was occluded, a sharper relatable angle was implied and a larger distance was required to be interpolated. For the square, only the size of the interpolated distance changed with gap size.

However, the similarity of our results for circles and squares in all seven experiments raises a second issue in itself. For circles, only gap sizes of 25% or less were relatable in the strict sense; the larger gap sizes all involved edge extensions that met at angles of less than 90°. The square shapes we used, on the other hand, were on the margin of the angle size limitation for all gap sizes, in that their extended edges met at exactly 90°. Nonetheless, the data suggested that both shapes were being completed over a fairly large range of gap sizes and that there was a similar change in completion time with gap size.

Finally, we note, along with others (e.g., Boselie & Wouterlood, 1992), that shape completion can occur even when the angle of the extended edges is much less than 90° (i.e., is not relatable). The triangle shape we tested in Experiment 1 (i.e., involving a nonrelatable angle of 60°) appeared to be completed in the same way as the square or the hexagon shapes. Thus, once again, there appears to be more to shape completion than can be explained by a single factor.

*Hybrid theories.* The failure of theories that are based on a single construct (i.e., either global simplicity or local edge relatability) to account for all shape completion argues in favor of theories with more parameters. One such theory has been developed by Boselie (1988; Wouterlood & Boselie, 1992). The local features that are critical in this theory are the family of possible three-edge junctions (i.e., arrows, *Y*s, and *T*s) and two-edge junctions (i.e., *L*s). The "best" local guesses are that (a) the line of least change at these junctions represents the edges of a common surface and (b) the convex side of an L-junction is the nearer of two overlapped surfaces. The global measure of form goodness essentially is borrowed from coding theory.

In this theory, global aspects of goodness (e.g., symmetry, good form) work together with, and are constrained by, local aspects (e.g., good continuation at edge junctions and intersections) to determine the eventual percept of an occluded shape. This permits the theory to make predictions even when the overall goodness of two shape alternatives has been made equal (the one with greater local goodness will win) or when the local goodness of two edge interpolation possibilities has been equated (the one with greater global goodness will win). However, Boselie (1988) and Wouterlood and Boselie (1992) also noted the limitations of their theory in predicting some display interpretations. A complete theory will likely have to make room for several top-down constraints (e.g., familiarity, coincidence, global symmetry) and more than one data-driven rule (e.g., angle relatability, spatial extent of interpolation).

*Form and color and depth (FACADE).* The one theory of shape completion that naturally predicts our gap size effects for occluded shapes is that of Grossberg (1987, 1994) and Grossberg and Mingolla (1985). Completion of both occluded edges and of subjective surfaces is accomplished via two perceptual processing modules that interact among themselves and contribute to a higher order object recognition module. The so-called *boundary contour system* uses long-range cooperative mechanisms to bridge gaps in edges in the image. According to Grossberg and Mingolla (1985), it "is capable of generating sharp boundaries, with sharp endpoints, across large spatial domains" (p. 149). One of the functions of the second module, the feature contour system, is to propagate surface qualities such as brightness, color, and texture to any enclosed boundary constructed by the boundary contour system. Note that because both systems use iterative and cooperative mechanisms to propagate visual information in a spatial representation, it is natural that they would take longer to complete a highly occluded shape than one that is less occluded. To the extent that this model adequately represents biological visual mechanisms, our data provide behavioral support for the existence of such propagation operations in human vision.

However, there is one qualification that bears mentioning. So far, the FACADE model seems designed to accomplish completion only for edges that are colinear. The model does not address the completion of shapes such as those studied here, whose extrapolated edges meet at a wide range of angles. Therefore, the match between data and theory is still not complete.

As this overview of theories shows (see also Table 1), our findings are difficult to reconcile with any single theory. In fairness to the theories, our data also are not based on a set of stimuli diverse enough to speak directly to the issue of exactly which constructs are required in a comprehensive theory. What they do show strongly, however, is that there are subtle aspects of the completion operation (e.g., the time for completion is related to the size of the area to be completed) that are amenable to study using the performance measures of RT and accuracy.

### *Future Directions*

We view our findings as a necessary first step in laying the foundation for a systematic study of shape completion. In particular, we have shown that (a) it is possible to study important aspects of this primitive perceptual process using performance measures, (b) the process is time and space dependent, and (c) the process is probably multifactorial in nature. These conclusions suggest several specific avenues for future research.

*Comparisons of subjective reports and performance measures.* Our experiments were inspired in many cases by previous reports in which the subjective reports of observers were the primary data. Although our data confirmed some of these observations (e.g., the primitive nature of completion), they also revealed aspects that did not appear to be accessible to introspection (e.g., the gap size effect). It thus would seem worthwhile to compare other claims. For example, observers often are asked to judge whether one or two depth planes are seen (Boselie, 1988; Boselie & Wouterlood, 1992) or which of two objects appears closer (Dinnerstein & Wertheimer, 1957). These tasks are especially well suited to the study of performance measures on such stimulus factors as local edge type and overall shape simplicity. Furthermore, these measures could be used in conjunction with exposure duration and masking manipulations to establish whether the stimulus variables were having their influence relatively early or late in the visual stream.

*Interactions of space and time.* Sekuler and Palmer (1992) suggested that the completion of a 25% occluded shape in a static pictorial display required at least 200 ms of processing time. Bruno et al. (in press) showed that this could be accomplished in less time if additional depth cues were provided. We found that RTs increased with the size of the area to be completed and that this effect was reduced with the additional cue of motion parallax. These interactions among time, space, and depth cues should be directly observable in a factorial study. For example, our tasks and designs could be repeated with variable exposure durations, the priming task of Sekuler and Palmer (1992) could be combined with gap size and depth cue manipulations, or both.

The issue of the appropriate spatial metric for completion also is worthy of further study. As mentioned earlier, we used the percentage of missing area as a measure of convenience, one that was surely related monotonically to almost any other measure of gap size. However, we also studied only surface shapes (as opposed to outline drawings) and shapes of a single size. Preliminary data from our laboratory indicate that the relevant size dimensions are scaled to the size of the display, not to their visual angle on the retina. This is consistent with what has already been shown for subjective surface and contour strength (Lesher & Mingolla, 1993; Shipley & Kellman, 1992b). Further studies are needed to increase the understanding of these issues, including studies comparing the amount of occluded edge versus occluded area and the relation between the size of the shape and the size of the occluded portion.

*Multicausal nature of shape completion.* It appears that the concept of shape completion, which once played host to a number of single-construct theories, must now be viewed as being multiply determined. Just as the perception of an object's depth in 3-D space is believed to be determined by many factors, some spatially local (pictorial cues such as T-junctions), others global (binocular disparity), and still others determined by experience (familiar size), so the perception of the shape of an occluded object is probably influenced by multiple factors. This suggests that factorial studies should be conducted in which both the relative contributions of various factors can be assessed (e.g., local continuation of edges, global good form, shape familiarity), as well as the nature of their interactions (e.g., cooperative, competitive, independent). Such factorial studies would have the salutory benefit of increasing the generality of the results over a much larger range of stimuli. At present, one of the main problems in comparing theoretical views is that the empirical support is based on different classes of stimuli.

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