Research Article

OBJECT-BASED VISUAL SELECTION: Evidence From Perceptual Completion

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Abstract—*A large body of evidence suggests that visual attention selects objects as well as spatial locations. If attention is to be regarded as truly object based, then it should operate not only on object representations that are explicit in the image, but also on representations that are the result of earlier perceptual completion processes. Reporting the results of two experiments, we show that when attention is directed to part of a perceptual object, other parts of that object enjoy an attentional advantage as well. In particular, we show that this object-specific attentional advantage accrues to partly occluded objects and to objects defined by subjective contours. The results corroborate the claim that perceptual completion precedes object-based attentional selection.*

The world consists of objects and surfaces. It is reasonable to suppose, therefore, that the human visual system has evolved to represent and operate on visual information in terms of objects and surfaces. Recent evidence supports this idea in showing that visual attention—the process of selecting a salient or task-relevant subset of visual information for deeper processing than the rest—can act on an object-based representation (e.g., Baylis & Driver, 1993; Duncan, 1984; Egly, Driver, & Rafal, 1994; Kahneman, Treisman, & Gibbs, 1992). This mechanism complements the well-documented ability to deploy attention to locations in space (e.g., Eriksen & Hoffman, 1972; Posner, Nissen, & Ogden, 1978).

Four classes of evidence support the notion that attention is sometimes object based. First, subjects can identify two attributes of a single object more efficiently than two attributes of two different objects, even when the objects in question are spatially superimposed (e.g., Baylis & Driver, 1993; Duncan, 1984; Kramer & Watson, 1996; Moore & Osman, 1993; Ward, Duncan, & Shapiro, 1996). Second, several well-known effects of attention have been found to apply to perceptual objects and not just spatial locations. These effects include inhibition of return (Tipper, Weaver, Jerreat, & Burak, 1994), repetition priming (Kahneman et al., 1992), negative priming (Tipper, Brehaut, & Driver, 1990), and repetition blindness (Chun & Cavanagh, 1997). Third, experiments have shown that visual elements that are perceptually grouped together tend to be attended together, even when spatial proximity is taken into account (e.g., Baylis & Driver, 1992; Driver & Baylis, 1989; Kramer & Jacobson, 1991; McLeod, Driver, & Crisp, 1988; Yantis, 1992; for a review of these and other relevant studies, see Egeth & Yantis, 1997). Finally, patients suffering from visual neglect have been found to exhibit an object-based frame of reference in their neglect behavior (e.g., Behrmann & Tipper, 1994; Driver & Halligan, 1991; Tipper & Behrmann, 1996). To the extent that neglect reflects a disruption of attentional mechanisms, these findings provide additional evidence for object-based attention.

A particularly clear example of object-based visual attention was reported by Egly et al. (1994). Subjects were shown displays that contained two rectangles (Fig. 1). The task was a simple reaction time task; subjects pressed a button as quickly as possible when they detected the onset of a white square. This target (i.e., the white square) could appear in any of the four ends of the two rectangles. Before the target was presented, one of the four locations was cued (the surrounding contours brightened for a moment). This cue informed the subject that when the target appeared, it was most likely to appear in that location. In fact, the target did appear in that location on 80% of the trials; these trials are referred to as *valid* trials. For the remaining 20% of the trials, however, the target appeared in a different location; these trials are referred to as *invalid* trials. Of the invalid trials, half were *same-object* trials and half were *different-object* trials. On the invalid same-object trials, the target appeared in the rectangle that had been cued, but at the end opposite the cue; thus, although the target was not in the cued location, it was in the cued object. On the invalid different-object trials, the target appeared in the other rectangle, but at the end that was closest to the cued location; thus, it was the same distance away from the cued location as targets on invalid same-object trials, but it was in a different object (Fig. 1). Any difference in response time between the invalid same-object condition and the invalid different-object condition would reflect an object-specific effect. If attention operates on objects, and not just on spatial locations, then one might expect an *object-specific advantage* in which responses are faster in the same-object condition than in the different-object condition. Egly et al. (1994) observed just such an object-specific advantage, providing further evidence for the idea that selective attention is, at least in part, object based.

In all the experiments cited so far, the objects in question were perceptually distinct, so there was no ambiguity in the image concerning which borders belonged to which objects (for an exception, see Behrmann, Zemel, & Mozer, in press). Under natural viewing conditions,

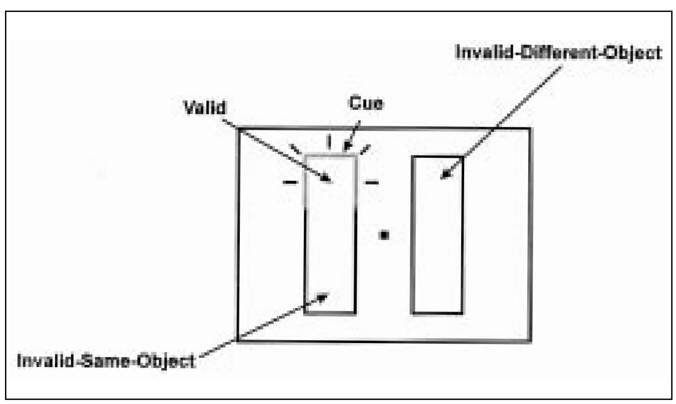

Fig. 1. Cartoon of the type of display and conditions that were used by Egly, Driver, and Rafal (1994) and in the present study (Experiment 1, no-occluder condition).

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however, objects are rarely this distinct. Objects exist in a three-dimensional world, yet the initial internal representation of visual scenes—the retinal image—is two-dimensional. As a result, the image of an object is often spatially fragmented. For example, an object can be partly occluded by other objects or by parts of itself. Figure 2a illustrates an example of perceptual completion of a partly occluded object; this is called *amodal* completion because the completed surface does not produce an explicit sensory experience. In addition, the lighting within a scene can create edges that correspond to no object boundary (e.g., shadows), or can accidentally render real object boundaries invisible. Figure 2b illustrates an example of perceptual completion of an object across an obscuring light region to form illusory contours. This is called *modal* completion because the perception of the completed surface is phenomenally experienced; that is, the edges between the inducing regions—edges that physically do not exist—produce an explicit sensory experience. These situations require perceptual-organization mechanisms to correctly group image elements into coherent object representations through perceptual completion (e.g., Kanizsa, 1979; Kellman & Shipley, 1991; Michotte, Thinès, & Crabbé, 1964/1991; Nakayama, He, & Shimojo, 1996; Yantis, 1995).

If attention is to be regarded as truly object based, then it should operate not only on object representations that are explicit in the image (such as the unoccluded rectangles on a differently colored background in the study of Egly et al., 1994), but also on representations that are the result of earlier perceptual completion processes, such as those illustrated in Figure 2. In this article, we report evidence that attention does operate on object representations that result from processes involved in the perceptual completion of fragmented or incomplete image information.

EXPERIMENT 1

In Experiment 1, we used displays that were inspired by those of Egly et al. (1994). To examine the role of perceptual completion on object-based attention, we added an occluding surface that required the partly occluded objects to be perceptually completed behind the occluding surface (amodal completion; Fig. 2a). To enhance the perception of occlusion, we presented the occluding surface stereoscopically so that it appeared to float in front of the depth plane containing the two occluded rectangles. The question addressed was whether object-specific effects of attention would be observed for objects that require completion behind an occluding surface.

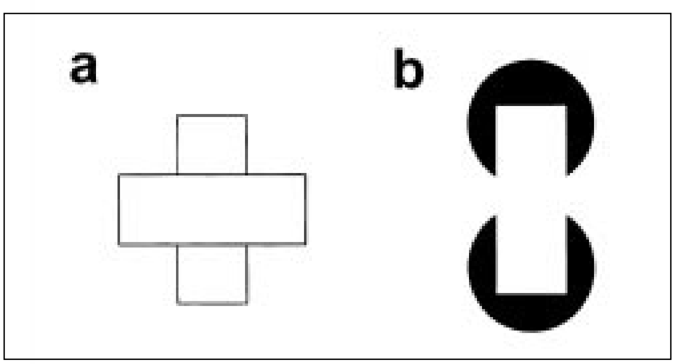

Fig. 2. Two types of perceptual completion: (a) amodal completion of an object (the vertical rectangle) behind an occluding surface (the horizontal rectangle) and (b) modal completion of an illusory object formed by illusory contours.

Method

Subjects

Seventeen young adults with normal or corrected-to-normal visual acuity and color vision participated in a single 1-hr session.

Equipment

Stimuli were presented on a VGA color monitor. Stereoscopic depth was simulated by a Vision Research Graphics pcStereoscope system, which alternated displays for the left and right eyes on the computer screen at a rate of 60 Hz (30 Hz per eye). These alternating displays were synchronized with the opening and closing of liquid-crystal shutters on goggles worn by the subject.

Stimuli

Displays consisted of two red rectangles with a luminance of 7.15 cd/m^2 and CIE coordinates of (0.628, 0.323). Each subtended a visual angle of $1.25° \times 3.75°$, and the two were separated (edge to edge) by 1.25° from the standard viewing distance of 55 cm. A white fixation cross ($0.4° \times 0.4°$) was centered between the rectangles. For half of the blocks (the *occluder* condition), displays included a third $4.6° \times 1.25°$ rectangle that was oriented orthogonally to the other two and was presented stereoscopically in front of them (crossed disparity of 0.26°). This third rectangle served as the occluding surface, behind which the other two rectangles had to be perceptually completed. (When the occluder was present, the central fixation cross was presented with the same disparity as that surface so that it appeared to be "on" the occluder, which was floating in front of the other two rectangles.) For the other half of the blocks (the *no-occluder* condition), no occluding rectangle was presented. For both the occluder and the no-occluder conditions, the two commonly oriented rectangles were oriented vertically for half of the blocks and horizontally for the other half.

In addition to the displays of rectangles, on each trial, four characters—three *T-L* hybrid characters and one *T* or *L*—were presented, one character centered at each of the four ends of the two commonly oriented rectangles. These stimuli were blue, with a luminance of 6.64 cd/m^2 and CIE coordinates of (0.153, 0.065). These characters subtended $0.73° \times 0.73°$ each and were randomly oriented at one of four orientations (0°, 90°, 180°, and 270°). Finally, cues consisted of the outline of one end of one rectangle changing to white (65.53 cd/m^2). The cue extended along the length of the rectangle for 1.25°. All stimuli were drawn with lines that were 0.05° thick.

Task

The task was two-alternative forced-choice letter identification. On each trial, four stimuli were presented. Three were distractors (a *T-L* hybrid character), and one was the target (a *T* or an *L*). The task was to report, as quickly as possible, whether the target was a *T* or an *L*, by pressing the left or right button, respectively.

Design

A 3 (validity: valid, invalid same-object, invalid different-object) × 2 (display type: no-occluder, occluder) design was used. (The design was also counterbalanced across blocks for rectangle orientation—horizontal and vertical—but the intent was to collapse across this variable.) Display type was manipulated between blocks of trials, and validity was manipulated within blocks of trials. Display type was defined as described in the *Stimuli* section. Validity was defined by the relationship between the location of the cue and the location of the target. In particular, valid trials were those on which the target and the cue appeared at the same location. Invalid same-object trials were those on which the target appeared in a different location than the cue, but within the same rectangle. Invalid different-object trials were those on which the target appeared in both a different location and a different rectangle than the cue. The target in this condition always appeared in the location of the uncued rectangle that was the same distance from the cue as a target in the invalid same-object condition would be (see Fig. 1). Eighty percent of the trials were valid trials; 10% were invalid same-object trials; and the remaining 10% were invalid different-object trials. Across the two orientations, there were 192 observations in the valid condition and 24 observations in each of the two invalid conditions, for both the no-occluder and the occluder conditions.

Procedure

Each subject participated in a single 1-hr session that began with a set of written instructions that described the task. The instructions emphasized that subjects should remain fixated on the central fixation cross throughout each trial and that they should direct attention to the cued location without moving their eyes.[1] Subjects were told that the target would appear in the cued location on most of the trials. They then completed a 16-trial practice block in which each type of display appeared. After practice, subjects completed 12 blocks of 40 trials each, from which the data were collected.

Figure 3 illustrates a typical trial. Each trial began with the presentation of the fixation cross and the two rectangles with or without the occluding rectangle, depending on the display condition. This display remained for 1 s. The cue was then flashed for 100 ms, and an interstimulus interval (ISI) of 200 ms followed. Finally, the stimuli (three distractors and one target) were presented. They remained present until a response was made, at which time the screen went blank.

Each error was followed by two 50-ms, 2-kHz beeps separated by 100 ms. In addition, the mean response time (RT) and percentage of trials correct were displayed on the monitor following each block.

Results

Figure 4 shows the mean RTs for correct responses, collapsed across orientation, for each of the two display types. Preliminary analyses confirmed that there was no significant main effect of rectangle orientation, and it did not interact significantly with either validity or display type. The collapsed data were submitted to a 3 (validity: valid, invalid same-object, invalid different-object) × 2 (display type: no-occluder, occluder) repeated measures analysis of variance (ANOVA). The main effect of validity was significant, $F(2, 32) = 47.8$, $p < .001$,

1. We did not monitor eye position in this experiment, leaving open the possibility that on some trials, subjects could have moved their eyes to the cued location before the target appeared. If this did occasionally occur, however, it would not have compromised the results that were relevant to our primary hypothesis, because the same- and different-object trials would have been affected to the same degree.

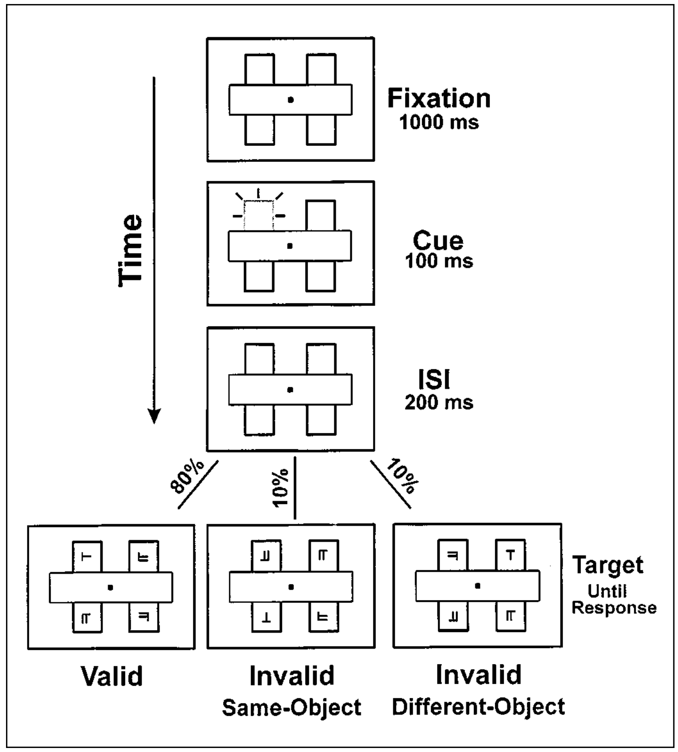

Fig. 3. Timing and trial events for Experiment 1. The figure shows the occluder condition only. In the experiment, the figures were light on a dark background. ISI = interstimulus interval.

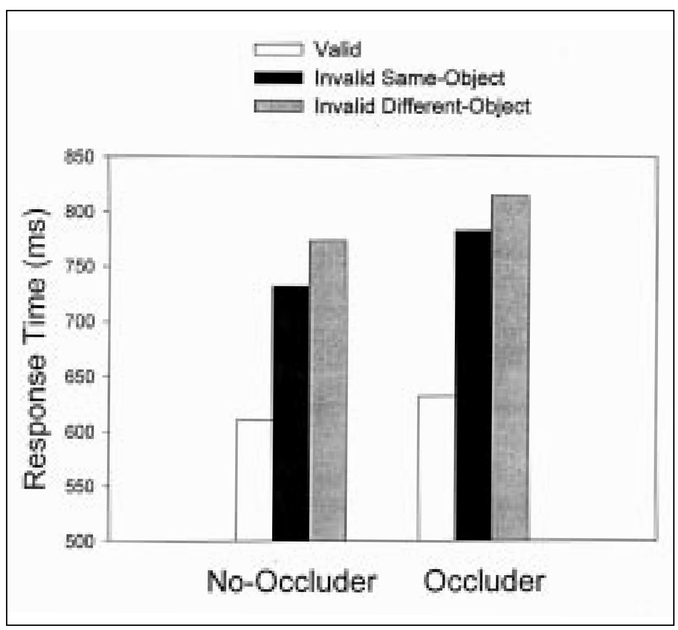

Fig. 4. Mean response times for correct responses for Experiment 1. These data are collapsed across the vertical and horizontal orientation conditions.

but that for display type was not, $F(1, 16) < 1$, n.s. The interaction between the two factors was also not significant, $F(2, 32) < 1$, n.s.

Planned comparisons confirmed that for both display conditions, RTs on valid trials were faster than those on both invalid same-object trials and invalid different-object trials. For the invalid same-object trials, the mean difference from valid trials in the no-occluder condition was 122 ms, $t(16) = 5.11$, $p < .001$, and the mean difference from valid trials in the occluder condition was 150 ms, $t(16) = 5.47$, $p < .001$. For the invalid different-object trials, the mean difference from valid trials in the no-occluder condition was 163 ms, $t(16) = 6.83$, $p < .001$, and the mean difference from valid trials in the occluder condition was 182 ms, $t(16) = 6.37$, $p < .001$. Moreover, with regard to the object-specific effects, for both display conditions, RTs on invalid same-object trials were faster than those on invalid different-object trials. For the no-occluder condition, the mean difference was 41 ms, $t(16) = 3.53$, $p < .01$; for the occluder condition, the mean difference was 32 ms, $t(16) = 2.46$, $p < .05$.

All of the same analyses were conducted on the arcsine transformations of the error rates (error rates are shown in Table 1). Only the effect of validity approached significance, $F(2, 32) = 2.38$, n.s.

Discussion

These results contribute to the growing body of evidence that attention is, under some circumstances, object based. Moreover, they reveal that object-based selection of partly occluded objects operates after the engagement of perceptual completion processes.

The results also rule out an alternative account for the results reported by Egly et al. (1994). One could argue that in their experiment, the same-object and different-object conditions differed in the amount of visual clutter occupying the space between the cued and uncued locations (see Fig. 1). In the different-object condition, there were two contours (the edges of the two rectangles) between the cued and uncued locations; in the same-object condition, there were no contours between the cued and uncued locations. These intervening contours could conceivably have interfered with the distribution of attention differentially in the two conditions. In the present experiment, visual clutter in the form of contours in the retinal image were equated across these two conditions and so could not explain the observed object-specific advantage.

EXPERIMENT 2

Experiment 2 provides another demonstration of an object-specific advantage for objects that require perceptual completion. In Experiment 2, the objects were defined by subjective contours, the form of perceptual completion known as modal completion (Fig. 2b). Two types of display were used, termed the *contour* (Fig. 5a) and *no-contour* (Fig. 5b) displays. The no-contour displays served as a control condition in which perceptual completion into rectangles should not have occurred. The no-contour displays were the same as the contour displays except that six bars were added, four closing off the openings of the inducing disks and two centered along the paths of the two pairs of inducing regions. The purpose of introducing these additional bars was to eliminate the formation of the subjective rectangles.[2]

Table 1. *Error rates (percentages) for Experiment 1*

	Validity		
Display	Valid	Invalid, same object	Invalid, different object
No occluder	2.3	4.2	3.3
Occluder	1.7	3.5	3.8

Method

Subjects

Sixteen new subjects were tested. They came from the same pool that provided the subjects in Experiment 1.

Equipment

Stimuli were presented on a 19-in. (48-cm) Taxan UV1150 color monitor controlled by an Artist Graphics XJS-1280 graphics board, and were viewed from a distance of 64 cm. The room was dimly lit with indirect incandescent lighting.

Stimuli

The inducing disks for both the contour and the no-contour conditions were light gray (22.03 cd/m^2), were presented on a dark background (0.22 cd/m^2), and subtended 2.77° in diameter. The edge-to-edge distance between the disks, both vertically and horizontally, was 3.33°. The rectangular cutouts in the inducing disks were 2.08° × 1.39° rectangles that were the same color as the background. The resulting perceptual rectangles were 1.39° × 7.48°. The gray bars used in the no-contour condition were 1.39° × 0.22°.

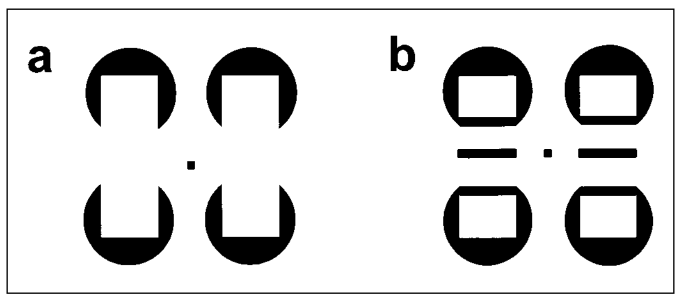

Fig. 5. Examples of the types of displays used in Experiment 2: (a) contour condition, in which two rectangles are formed through modal completion, and (b) no-contour condition, in which the completion process is disrupted. In the experiment, the figures were light on a dark background.

2. We included the middle bars to help eliminate the illusory contours (Peterhans & von der Heydt, 1989). Without them, the rectangular cutouts were sometimes perceived as objects that were created through amodal completion. Specifically, the inducing disks appeared as apertures in a dark surface (white in Fig. 5), and the cutouts were parts of rectangles extending behind that dark surface. The bars in the middle reduced the tendency toward amodal completion. Following the experiment, we asked some of the subjects informally if they perceived the cutouts as completed rectangles in the no-contour condition. None said that they did; the results corroborate these reports.

Cues consisted of three red line segments—one horizontal (1.45°) and two vertical (2.14°)—that corresponded to the opening of a given inducing disk. The lines were 0.18° thick and extended outward from the illusory rectangle into the gray inducing region, and did not extend beyond the inducing disk at the bottom.

Finally, the distractors and target were blue, with a luminance of 6.82 cd/m^2 and CIE coordinates of (0.145, 0.077). They subtended 0.67° × 0.67°. They were the same as those in Experiment 1 in all other respects.

Task

The task was the same as that in Experiment 1.

Design

A 3 (validity: valid, invalid same-object, invalid different-object) × 2 (display: contour, no-contour) design was used. (As in Experiment 1, the design was also counterbalanced across blocks for rectangle orientation—horizontal and vertical—but the intent was to collapse across this variable.) Display was manipulated between blocks of trials, whereas validity was manipulated within blocks of trials. Validity was defined as in Experiment 1. For the no-contour condition, with the openings of the inducing regions interrupted, all four locations were perceived as distinct regions or objects. Although the labels "invalid same-object" and "invalid different-object" are therefore misnomers, the distinction between these conditions provides a control for other features of the display, such as the orientations of the openings of the inducing regions. Across orientations, there were 256 observations per subject in each of the valid conditions and 32 observations per subject in each of the invalid conditions.

Procedure

The procedure was the same as that of Experiment 1, except that the practice block was 60 trials long and data were collected from eight blocks of 80 trials each.

Results

The mean RTs for correct responses in the experimental and control conditions, collapsed across orientation, are shown in Figure 6. Preliminary analyses showed that there was no main effect of orientation and that it did not significantly interact with either validity or display type. The collapsed data were submitted to a 3 (validity: valid, invalid same-object, invalid different-object) × 2 (display: contour, no-contour) repeated measures ANOVA. The main effect of validity was significant, $F(2, 30) = 79.44$, $MSE = 9{,}023.79$, $p < .01$, but that for display type was not, $F(1, 15) = 0.04$, $MSE = 1{,}400.95$, n.s. The interaction between validity and display type was significant, $F(2, 30) = 4.31$, $MSE = 683.53$, $p < .05$, indicating that the validity manipulation had different effects in the contour and no-contour conditions.

Planned comparisons confirmed that, for the contour condition, RTs on valid trials were faster than those on both invalid same-object trials and invalid different-object trials. For the invalid same-object trials, the mean difference was 169 ms, $t(15) = 8.48$, $MSE = 56.65$, $p < .01$. For the invalid different-object trials, the mean difference was 198 ms, $t(15) = 9.06$, $MSE = 61.68$, $p < .01$. More relevant to the current hypothesis, RTs on invalid same-object trials were faster than RTs on invalid different-object trials, with a mean difference of 28 ms, $t(15) = 3.62$, $MSE = 22.77$, $p < .01$.

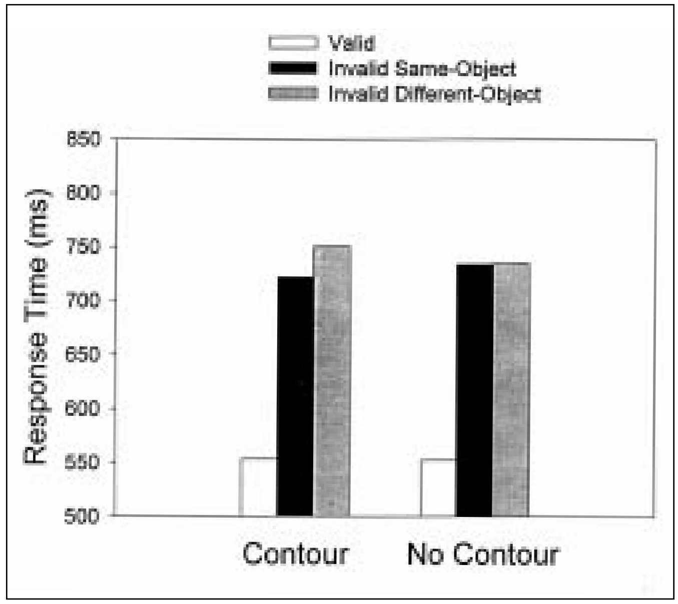

Fig. 6. Mean response times for correct responses in Experiment 2. These data are collapsed across the vertical and horizontal orientation conditions. Note that in the no-contour condition, the distinction between same-object and different-object conditions is made merely for comparison to the corresponding contour conditions. See the text for details.

For the no-contour condition, RTs were also faster on valid trials than on both "invalid same-object" trials and "invalid different-object" trials. For the "invalid same-object" trials, the mean difference was 182 ms, $t(15) = 8.96$, $MSE = 57.29$, $p < .01$. For the "invalid different-object" trials, the mean difference was 183 ms, $t(15) = 9.03$, $MSE = 57.33$, $p < .01$. However, unlike in the experimental condition, there was no reliable difference between RTs on "invalid same-object" trials and on "invalid different-object" trials, with a mean difference of 1 ms, $t(15) = 0.18$, $MSE = 3.91$, n.s.

All of the same analyses were conducted on the arcsine transformations of the error rates (error rates are shown in Table 2). No significant effects that were in a different direction than those observed in the RTs were revealed.

Discussion

Experiment 2 provides further evidence that attention operates, at least in part, on an object-based representation. Moreover, Experiment 2

Table 2. *Error rates (percentages) for Experiment 2*

	Validity		
Display	Valid	Invalid, same object	Invalid, different object
Contour	1.1	2.3	3.3
No contour	1.5	4.4	2.9

provides another example of an object-specific advantage for objects that require perceptual completion. Thus, object-specific effects of attention are not limited to objects that are spatially unfragmented, such as those in Figure 1.

GENERAL DISCUSSION

The purpose of the research reported here was to examine whether the effects of object-based attention extend to object representations that require perceptual completion. Experiment 1 demonstrated such an extension to objects that required perceptual completion of a partly occluded object, and Experiment 2 demonstrated such an extension to objects that required perceptual completion of subjective contours. These extensions of object-based effects are important because many (if not most) objects in natural scenes require some form of perceptual completion. Thus, in order for object-based models of attention to be appropriate explanations of real-world visual processing, object-based effects must extend to objects that require perceptual completion.

One implication of the present results is that the processes that give rise to perceptual completion must begin before object-based attention performs its selective function. Specifically, before an object can be selected, some representation of that object must exist. If the object requires perceptual completion, then it follows that the completion process must be engaged before attention can select that object. This interpretation is corroborated by evidence that perceptual completion processes appear to be obligatory. Both modal and amodal completion seem to have occurred even when inhibiting those completion processes would have improved performance on the visual search tasks in which they were tested (Davis & Driver, in press-a; Rensink & Enns, in press; He & Nakayama, 1992). Because these completion processes appear to be obligatory, it has been argued that they probably occur early within the stream of visual information processing. This position is consistent with our findings, which require that perceptual completion processes at least begin before object-based attention performs its selective function (see also Davis & Driver, 1997). Note also that in our experiments, the scene was available for inspection for 1 s before the critical trial events (i.e., presentation of the cue and target) began. We assume that this provided sufficient time for the spatial layout of surfaces to be apprehended and for perceptual completion to generate coherent object representations.

Together with results from visual search tasks, our finding that when a given location is cued, the effects of that cue seem to spread to other locations within the cued object—even when that object requires perceptual completion—converges with results from other tasks involving selection. Behrmann et al. (in press), for example, found that observers more rapidly judged whether two features of a display were the same or different when they were part of one object than when they were parts of two different objects, even though the object required completion behind an occluding surface. Similarly, Davis and Driver (in press-b) found that the interfering effect of a distracting stimulus was greater when the distractor appeared on the same object as the target than when the distractor appeared on a different object. Again, this occurred even though the object required perceptual completion—modal completion, in this case. Both of these sets of results are consistent with the claim that attention selects objects even when the objects require perceptual completion (for a related result, see Chen, in press).

The present results suggest that object-based attention operates on perceptual objects that require perceptual completion. This result corroborates claims that perceptual completion occurs early in vision and serves to create candidate object representations for the allocation of attention within the visual scene (Davis & Driver, in press-a; Rensink & Enns, in press; He & Nakayama, 1992). Our results also converge with other recent demonstrations of object-based attentional effects involving perceptually completed objects (e.g., Behrmann et al., in press; Davis & Driver, in press-b). Because partial object occlusion is the rule rather than the exception in natural scenes, object-based selection of perceptually completed objects is functionally well motivated. When viewing a dangerous predator that is partly occluded by heavy foliage and shadow, a visually guided organism would do well to attend to the entire animal rather than mistake its parts for distinct perceptual objects.

Acknowledgments—This research was supported by National Institutes of Health (NIH) Grant R01-MH43924 awarded to S.Y. and NIH Grant 5 T32 MH18215 awarded to the Department of Psychology, Johns Hopkins University. We are grateful to two anonymous reviewers for helpful comments.

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(RECEIVED 4/8/97; ACCEPTED 8/11/97)