The spread of attention to hidden portions of occluded surfaces

CATHLEEN M. MOORE and CHRISTOPHER FULTON
Pennsylvania State University, University Park, Pennsylvania

We report two experiments in which the two-rectangles method of Egly, Driver, and Rafal (1994) was used to test whether object-specific attentional cuing advantages can spread to hidden portions of occluded objects. Displays began with portions of two rectangles hidden by a third, occluding object. One end of one of the two rectangles was cued, after which the occluder rotated around its center point and target stimuli were presented. In one condition, the occluder was removed from in front of the other objects, either by rotating away from them (Experiment 1B) or by rotating and then slipping behind them (Experiment 1B). In another condition, the occluder first rotated away but then returned to its original position. In both experiments, an object-specific cuing advantage occurred in the occluder-removed condition for targets that appeared in what had been hidden locations of the cued object. No analogous advantage occurred in the occluder-returned condition.

Visual attention refers to the mechanism by which some visual information in a scene is selected for deeper or more efficient processing than other information is. A central question has concerned the representational basis for visual selection. Two contrasting, although not mutually exclusive, possibilities have been considered. One is that attention is allocated to a subset of spatial locations within the visual field (e.g., Eriksen & Hoffman, 1972; Posner, 1980). The second is that an object is selected from a scene that has been perceptually parsed into multiple object representations (e.g., Duncan, 1984).

A method developed by Egly, Driver, and Rafal (1994), which we will refer to as the *two-rectangles method*, has been used extensively to demonstrate that visual attention seems to be both location based and object based. Subjects were shown displays containing two parallel rectangles, and their task was to detect the onset of a target (a white square) that could appear in any of the four ends of the two rectangles. Before the target appeared, one of the four possible target locations was cued, indicating to the subjects that the target was more likely to appear in that location than in any other and that the subjects should, therefore, attend to that location. Responses were fastest to targets appearing in the cued location, consistent with information being selected on the basis of location. The next fastest set of responses were those to targets that appeared in the opposite end of the rectangle that contained the cued location, consistent with

information being selected on the basis of objects within the scene.

Moore, Yantis, and Vaughan (1998) noted that if the object-specific effect that is observed in the two-rectangles method reveals characteristics of selecting object representations, it should be observable even when the objects in question require perceptual completion behind an occluding surface. They tested this prediction by presenting two parallel rectangles, with a third, orthogonal rectangle presented in front of the first two, thus requiring that the first two be perceptually completed in order to exist as perceptual objects. Despite the need to perceptually complete the two rectangles, both location-specific and object-specific cuing effects occurred, just as in the unoccluded two-rectangles experiments. Behrmann, Zemel, and Mozer (1998) tested the same idea, using a same-different matching task. They found that stimuli that were perceived as part of the same object were compared more efficiently than were comparable stimuli that were perceived as parts of different objects, even when the object required perceptual completion behind an occluding surface (see also Pratt & Sekuler, 2001; Zemel, Behrmann, Mozer, & Bavelier, 2002). Thus, object-specific effects appear to extend to objects that require perceptual completion.

The present study extends the question of the spread of attention within occluded objects to ask whether a within-object selection advantage can extend to hidden regions of occluded objects. Specifically, we ask whether a cuing advantage can spread from one part of an occluded object to an invisible part of the object—invisible insofar as it is behind the occluder and only implied in the perceptual representation of the object. This question is of interest because an occluded part of an object is a meaningful construct only at a level of representation in which the scene has been perceptually parsed into objects; it does not exist as such in the image. To the extent that

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those portions of the object are selected, it provides strong evidence that the attentional selection system acts, at least in part, within scene-level representations.

The literature is mixed with regard to the question of whether cuing effects spread to regions of the scene that occlude cued objects. To the extent that selection is object specific, one would expect that occluders should not be selected along with the cued object, because, they are separate objects from those that they occlude. Consistent with this expectation, Davis and Driver (1997a, 1997b) found that when a cued rectangle was occluded by another object, the part of the occluder that fell on top of the cued rectangle showed no processing advantage. This was true despite the fact that the occluding region fell in line with the cue (cf. Avrahami, 1999). In contrast, using a variation of the two-rectangles method, Haimson and Behrmann (2001) found that the cuing advantage spread along the contours of a cued object regardless of whether the particular locations in the image were depicted as part of the cued object or as part of an occluding object. A difference between the studies is that Davis and Driver used binocular disparity to reinforce the perception that the occluding surface really was an occluding surface separated in depth from the cued object, whereas Haimson and Behrmann used only monocular pictorial cues (e.g., T-junctions) to depict occlusion. Haimson and Behrmann reasoned that perhaps information was selected on the basis of spatial location in all cases, but in the Davis and Driver studies, the binocular disparity afforded more of an opportunity to include the *z*-dimension (i.e., depth) in defining that subset of locations than did the static pictorial cues alone. This possibility is considered further in the General Discussion, where the results from the present study are taken into account as well.

Although studies have been conducted to ask whether attention can extend from one visible part of an occluded object to another (Behrmann et al., 1998; Moore et al., 1998; Pratt & Sekuler, 2001; Zemel et al., 2002) and studies have been conducted to ask whether cuing advantages extend to occluding regions of objects that occlude cued objects (Davis & Driver, 1997a, 1997b; Haimson & Behrman, 2001), the question of what happens with the hidden parts of occluded objects has yet to be addressed. We did so using the two-rectangles method with displays that were similar to those used by Moore et al. (1998, Experiment 1). Specifically, a third, occluding rectangle was placed diagonally across different ends of the two rectangles (see Figure 1). After cuing a location, the occluder rotated away from its original position to reveal what had been occluded portions of the two rectangles. This allowed us to probe whether the advantage of the cue can extend even to those portions of the objects that were occluded at the time of the cue and, therefore, did not exist at the image level of the display at the time at which attention was allocated within the scene.

We conducted two experiments that differed in the type of motion that was used to reveal the occluded por-

Figure 1. Illustration of occluder position conditions in Experiment 1A (panel A) and Experiment 1B (panel B). In both experiments, the occluder-removed condition revealed positions of the main rectangles that had been occluded at the time of the cue. These are compared with the same physical position in the occluder-returned condition, where the position is now depicted as one on the occluder, not as one on one of the main rectangles.

tions of the objects (see Figure 1). In Experiment 1A (Figure 1A), the occluder either rotated away from its original position and continued until it was parallel to the

other two rectangles (*occluder removed*) or rotated away and then retraced its steps so that it ended up back in its original occluding position (*occluder returned*). In Experiment 1B (Figure 1B), the occluder rotated away from its original position and then retraced its steps in both conditions. In the occluder-removed condition, it slipped behind the other two rectangles, whereas in the occluder-returned condition, it slipped back in front of the two other rectangles into its original position. The occluder-removed condition in both experiments allowed us to probe what had been a hidden portion of the cued object at the time of the cue, and the occluder-returned condition provided a control in which no cuing advantage was expected because the location was on the occluding object, not on the cued object.

To preview the results, object-specific cuing effects did extend to the occluded portions of cued objects. In both experiments, there was a cuing advantage for what had been occluded positions of the cued object in the occluder-removed condition. No reliable advantage for the same image-level positions occurred when the occluder had been rotated back into place in the occluder-returned condition.

METHOD

Subjects

Fifty individuals, ranging from 18 to 27 years of age, were tested in two experiments, 25 in each. All the subjects reported normal or corrected-to-normal visual acuity, and all were naive as to the purpose of the experiment.

Equipment

Stimuli were presented on a 21-in. Nanao FlexScan F2-21 EX color monitor. Trial events and data collection were controlled by a PC with a Pentium II processor. Responses were collected on a standard keyboard.

Stimuli

Initial displays consisted of two 12.4×3.3 degrees of visual angle (dva) rectangles that were oriented vertically for half the blocks and horizontally for the other blocks. These rectangles were positioned so that the outer-edge-to-outer-edge distance was 12.4 dva, the same distance as the length of the rectangles. A third 18.0×3.8 dva diagonal rectangle, oriented at $+45^\circ$ for half the trials and -45° for the other half, occluded opposing ends of first two rectangles (see Figure 1). There was also a red 0.8-dva radius fixation circle centered on the occluder in the center of the display. Cues consisted of the outline of one end of one rectangle changing from gray to white and thickening by 1 pixel. It extended along the length of the rectangle for 3.3 dva.

Occluder motion in Experiment 1A. In the occluder-removed condition, the occluder rotated around its center point away from its original position in eight steps. The steps were approximately 5.6° each, so that the occluder ended up parallel with the other two rectangles, occluding no part of them. In the occluder-returned condition, the occluder rotated around its center point away from its original position in four 5.6° steps and then retraced those steps, so that it ended up back in its original position. Each frame was presented for 100 msec, and the interstimulus interval was zero; the rectangle was in motion for a total of 800 msec in both conditions.

Occluder motion in Experiment 1B. The occluder-returned condition was identical to that in Experiment 1A. The occluder-removed condition was the same as the occluder-returned condi-

tion, except that as the occluder returned to its original position, it was drawn behind the other two rectangles, instead of in front. All intermediate positions of the occluder that overlapped the two main rectangles were drawn so that the diagonal one appeared behind the overlapping portions of the other two rectangles.

The targets and distractors in both experiments were blue $1^\circ \times 1^\circ$ uppercase Ts and Ls (the targets) and a T/L hybrid character that resembled a backward F (the distractor). The stimuli appeared at the center of the four ends of the two rectangles, so that the center of the letter was 1.43 dva from the end. This placed them entirely within the area of the occluding rectangle, when it was in place. Each stimulus was presented randomly at one of four orientations (0° , 90° , 180° , or 270°).

Design

A 3 (validity: valid, invalid "same," or invalid different) $\times$ 2 (occluder position: removed or returned) $\times$ 2 (display orientation: horizontal or vertical) within-subjects design was used in both experiments. Cues appeared at each of the four locations equally often. Both cue validity and occluder position were manipulated within blocks of trials. Occluder conditions were as described above. *Valid* trials were those on which the target and the cue appeared at the same location. *Invalid "same"* trials were those on which, for the occluder-removed condition, the target appeared in what would have been the completed part of the cued rectangle. Thus, in the occluder-removed condition, it was within the cued object, but in the occluder-returned condition, it was within a different object (see Figure 1); this distinction is the reason for the quotation marks around "same" for this condition label. Finally, *invalid different* trials were those on which the distance from the end of the uncued rectangle in which the target appeared to the cue was equal to the distance from the opposite end of the cued rectangle to the cue. Eighty percent of the trials within a block were valid trials, 10% were invalid "same" trials, and the remaining 10% were invalid different trials. Display orientation was manipulated between blocks of trials; for half of the blocks, the two parallel rectangles were oriented horizontally, and for the other half, they were oriented vertically. Block order was counterbalanced across subjects. No effect of orientation was expected; the intent was to collapse the data across the two orientation conditions, the order of which was counterbalanced across subjects.

Data were collected for each subject from eight blocks of 80 trials each. Collapsing across orientation, this resulted in 256, 32, and 32 observations per subject for the valid, invalid "same," and invalid different conditions, respectively, in each of the two occluder position conditions. Error trials were not repeated.

Procedure

Each subject was tested individually in a single 1 h session. The experiments began with a set of written instructions. The instructions described the task and emphasized that the subjects should remain fixated on the central fixation square throughout the trial and that they should direct their attention to the cued location. The subjects were told that the target would appear in the cued location on most of the trials.

The subjects first completed two 15-trial practice blocks, one in which the paired rectangles were vertical and one in which they were horizontal. After practice, the subjects completed the eight experimental blocks from which the data were collected.

Each trial began with the presentation of the central fixation square and the two rectangles with the occluder in its original position for 1,000 msec. The cue was then flashed for 100 msec and the motion of the occluder was initiated 50 msec later. The target and three distractors were presented in the ends of the two rectangles 200 msec after the occluder came to rest. These remained until a response was made, at which time the screen went blank. The subjects were instructed to respond as quickly as possible while maintaining an accuracy level of 90% or higher. Trial-by-trial error feedback consisted of a 500-msec, 256-Hz tone and a 2,000-msec blank

screen time out following each error. In addition, the mean response time (RT) and percentage of trials correct for the preceding block was displayed following each block.

RESULTS

Generally, the results suggest that an object-specific cuing advantage can extend to hidden portions of occluded objects. Table 1 gives the mean RTs and error rates (ERs) from both experiments.

Separate repeated measures analyses of variance (ANOVAs) were conducted on the subject means for each of the two experiments. Alpha was set at .05 for these and all other analyses reported here. For both experiments, the main effect of validity was significant [Experiment 1A, $F(2,48) = 52.0$, $MS_e = 5,764$; Experiment 1B, $F(2,48) = 42.6$, $MS_e = 5,870$]. The main effect of occluder position was not reliable in Experiment 1A [$F(1,24) = 1.7$, $MS_e = 566$] but was in Experiment 1B [$F(1,24) = 5.4$, $MS_e = 428$].¹ Most relevant to the question at hand, the interaction between validity and occluder type was significant in both Experiment 1A [$F(2,48) = 4.6$, $MS_e = 495$] and Experiment 1B [$F(2,48) = 5.2$, $MS_e = 395$].

Planned contrasts were conducted to assess the location-specific effect (valid vs. invalid "same") and the object-specific effects (invalid "same" versus invalid different) in the two experiments. The details of these analyses are given in Tables 2 and 3 for Experiments 1A and 1B, respectively. In general, they confirmed that for both experiments, there was a reliable location-specific cuing effect, regardless of occluder position. Specifically, responses to targets in the valid condition were faster than those in the invalid "same" condition in all cases. In contrast, the object-specific cuing effect depended on occluder position. Specifically, responses were faster in the invalid "same" condition than in the invalid different condition only when the occluder was removed to reveal what had been the occluded part of the cued object; responses were not reliably slower, however, in the invalid "same" condition when the occluder returned to cover the cued object. Thus, an object-specific cuing effect occurred for locations that had been hidden by the occluder at the time of the cue, but when the identical spatial location appeared to be part of the occluder itself, no reliable cuing advantage occurred.

All of the same analyses were conducted on the arcsin transformations of the ERs. There was no significant effect that was in a direction different from that for the RTs.

DISCUSSION

The results from these two experiments indicate that object-specific attentional cuing advantages can extend to hidden portions of occluded objects. An object-specific advantage occurred for targets that appeared in parts of cued objects that had been hidden at the time of the cue, and this advantage did not extend to the surfaces of occluding objects that occupied the same two-dimensional region of the scene. These results, then, provide further evidence that attentional selection occurs, at least in part, within organized representations of scenes, where *organized* means that the scene has been parsed and grouped into component objects and *selection within* these representations means that the organized components serve as the operands for selection. The hypothesis that attentional selection occurs within organized representations has already received considerable support (e.g., Duncan, 1984; Kahneman & Henik, 1981; see Driver & Baylis, 1998; Driver, Davis, Russell, Turatto, & Elliot, 2001, and Scholl, 2001, for recent reviews). The present study contributes to this body of evidence, in that it has demonstrated selection for aspects of the representation that are meaningful only if one is talking about an organized representation.

The fact that no advantage was observed in the occluder-returned condition makes it difficult to argue that the object advantage was caused by the invalid "same" location being aligned with the cued location, which has been shown to be a powerful modifier of the effect in the standard two-rectangles method (Avrahami, 1999). This follows because that location was aligned with the cued object in both the occluder-removed condition and the occluder-returned condition, yet a cuing advantage occurred only in the occluder-removed condition. It is true that in the occluder-returned condition, the location of interest was separated from the cue by lines that intersected the cued object and was, thereby, blocked off at an image level from the cue (see Figure 1). However, because it has been found that intersecting lines of that sort do not disrupt the object effect in variations of the two-rectangle method (e.g., Driver & Baylis, 1998; Mararra

Table 1
Mean Response Times (RTs, in Milliseconds) and Error Rates
(ERs, in Percentages) in Experiments 1A and 1B

Condition	Experiment 1A				Experiment 1B			
	Occluder Removed		Occluder Returned		Occluder Removed		Occluder Returned	
	RT	ER	RT	ER	RT	ER	RT	ER
Valid	517	2.9	524	2.6	526	1.9	536	2.2
Invalid "same"	636	6.1	653	6.1	637	3.6	657	4.9
Invalid different	668	6.4	658	7.0	661	4.3	655	4.9

Table 2
Details From Specific Response Time Comparisons: Experiment 1A

	Mean Diff (msec)		<i>t</i> (19)		SEM	
	Occluder Removed	Occluder Returned	Occluder Removed	Occluder Returned	Occluder Removed	Occluder Returned
"Same"—valid	119*	129*	6.72	7.00	17.66	18.41
Different—"same"	32*	5	2.72	0.62	11.78	8.60

*Significant ($\alpha = .05$).

& Moore, 2003; Moore et al., 1998; Pratt & Sekuler, 2001), this does not seem sufficient to account for the difference between the cuing advantages across the two conditions.

With that said, however, a qualification of our main conclusion must be noted. Assuming that object-specific cuing advantages emerge from something like a *spreading* of attention from the cued end of the object to the uncued end of it (cf. Shomstein & Yantis, 2002) and this spreading takes time, there is an alternative interpretation of the present results. That is that the object-specific advantage in the occluder-removed conditions arose from attention having spread through the cued object, at least partly, during the time in which the occluder had rotated away and the cued object was represented explicitly in the image, not just implicitly through amodal completion. Note, however, that even if this were the case, the fact that no analogous cuing advantage occurred in the occluder-returned condition indicates that the hidden portion of the occluded object was the representation that was selected, not the two-dimensional space in the image that it occupied. This follows because if it had been the two-dimensional space that was selected, a similar advantage would have occurred for targets at that location regardless of the occluder's position following rotation. Thus, the strength of the argument comes from the combination of an effect for the revealed location and a lack of an effect for the occluded location.

We now return to the contrast between Haimson and Behrmann's (2001) finding that a cuing advantage did spread to occluding regions of the scene, on the one hand, and Davis and Driver's (1997a, 1997b) and the present study's finding that a cuing advantage did not spread to occluding regions of the scene, on the other hand. We agree with Haimson and Behrmann's assessment that the quality of the cues to depth probably plays a big role in determining which of these findings attains. As has been noted, they used displays in which depth was depicted only through static pictorial cues, such as

T-junctions, whereas Davis and Driver included binocular disparity cues to depth. The present displays included accretion and deletion of the rectangles behind the moving occluders, which, like binocular disparity, may have provided relatively strong cues to depth, thereby affording greater opportunity to select a subset of information that was defined in depth, as well as in the picture plane.

Recall that Haimson and Behrmann's (2001) interpretation of the conflicting results, which the present results can be accommodated within, is that perhaps information is selected on the basis of spatial locations in all cases and that, with strong cues to depth, the *z*-dimension (i.e., depth) is more likely to be included in the selected representation. This explanation appeals to a distinction in the literature between *grouped array* representations of objects versus *space-invariant* representations of objects (Vecera, 1994; Vecera & Farah, 1994). Grouped arrays are spatial representations in that they are subsets of spatial locations, perhaps including depth in the definition. They are, however, organized to reflect relevant components of the scene. Grouped arrays are contrasted with spatially invariant representations of objects, which are representations that are independent of the spatial location(s) in which the objects appear. Despite the clarity of the distinction between grouped arrays and space-invariant representations (e.g., Cave & Bichot, 1999; O'Grady & Müller, 2000; Weber, Kramer, & Miller, 1997), the distinction that is highlighted in most studies concerned with *object-based attention* is not this one. Rather, the distinction of concern is between the selection of perceptually organized information and the selection of information from an arbitrary set of *xy* and, perhaps, *z* coordinates in the visual field, such as the spotlight metaphor suggests (see Driver, et al., 2001, for a review). Note that neither of these alternatives is necessarily space invariant, and it is this distinction that the present data weigh in on. In particular, they indicate that the selection process can be influenced by the organization of the scene even to the point of taking into account

Table 3
Details From Specific Response Time Comparisons: Experiment 1B

	Mean Diff (msec)		<i>t</i> (19)		SEM	
	Occluder Removed	Occluder Returned	Occluder Removed	Occluder Returned	Occluder Removed	Occluder Returned
"Same"—valid	111*	121*	6.07	6.00	18.31	20.31
Different—"same"	24*	2	3.77	0.20	6.41	7.34

*Significant ($\alpha = .05$).

“invisible” portions of perceptual objects. As has been suggested by Haimson and Behrmann (2001), the extent to which the selection system does this is likely to depend on the quality of the cues indicating a particular organization.

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NOTE

1. We had no a priori predictions concerning the overall effect of occluder position and do not have a specific explanation for the effect in Experiment 1B. Inspection of the means reveals nothing apparently different about the patterns in Experiments 1A and 1B. Rather, responses in both experiments were slightly slower overall in the occluder-retained condition than in the occluder-removed condition (5 msec in Experiment 1A and 8 msec in Experiment 1B). This difference happened to be significant in Experiment 1B. Because the difference was similar across experiments but was significant in one and not in the other, and because it was so small, we cannot draw any substantive conclusions from it.

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