

The Space of an Object: Object Attention Alters the Spatial Gradient in the Surround

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Although object-based attention enhances perceptual processing of information appearing within the boundaries of a selected object, little is known about the consequences for information in the object's surround. The authors show that distance from an attended object's center of mass determines reaction time (RT) to targets in the surround. Of 2 targets in the surround, both equidistant from a cue, the target closer to the center of mass was detected faster. Moreover, RT was shown to be a linear function of distance from the center of mass of a fixed, attended object, and changes to the shape of the object and its center of mass predictably altered RT. Object-based attention leads to a pattern of facilitation in the surround that may contribute to the organization of visual scenes.

Keywords: object-based attention, spatial attention, attentional gradients, visual perception

Attending to a spatial location in the visual field facilitates perceptual processing of information at that location (Posner, 1980), and concomitant enhancement of activity in neurons corresponding to those locations is observed in retinotopically mapped early visual cortex (Heeger, Gandhi, Huk, & Boynton, 2001; McMains & Somers, 2004; Tootell et al., 1998). Not only does the attended location enjoy psychological and neural facilitation, neighboring locations appear to benefit as well. In studies quantifying the spatial distribution of information facilitation (C. J. Downing & Pinker, 1985; Hoffman & Nelson, 1981; LaBerge, 1983), a smooth gradient in both the two- and three-dimensional spatial profiles is noted rather than a sharp boundary between attended and unattended locations (Ghirardelli & Folk, 1996; Henderson & Macquistan, 1993; Kim & Cave, 1995), and event-related potential recordings support this spatial pattern of distance-based facilitation (Mangun & Hillyard, 1988).

Biased competition accounts of attentional selection explain the mechanism underlying this space-based facilitation in terms of local competition between neurons whose responses are driven by similar aspects of the incoming stimuli (Desimone & Duncan, 1995). In early visual cortex, the spatial location of a stimulus is critical, and hence, neurons whose receptive fields overlie the location of a stimulus gain a competitive advantage over other

neurons in the region. Of note, neurons whose receptive fields are nearby or partially overlap with the stimulus also gain some advantage (Desimone, 1999). As the competition settles, a smooth gradient of activity mirroring the observed behavioral facilitation will form, with its peak centered on neurons whose receptive fields completely overlap with the stimulus.

This account can also be generalized to explain object-based attention (OBA) effects. Object-based facilitation is reflected in the enhanced processing of attributes of an attended object (e.g., color and shape); observers are faster and more accurate at reporting multiple properties from a single object than from two objects (Barenholtz & Feldman, 2003; Behrmann, Zemel, & Mozer, 1998; Duncan, 1984), and cortical areas mediating processing of these properties are coactivated (Martinez, Ramanthan, Foxe, Javitt, & Hillyard, 2007; O'Craven, Downing, & Kanwisher, 1999; Schoenfeld et al., 2003). Object-based effects have also been observed in attentional capture (Shomstein & Yantis, 2002) and inhibition of return (Heather & Tipper, 1999; Tipper & Weaver, 1998). Enhancement of the neural signals associated with the attended object has also been recorded from early visual cortex in monkeys (Khayat, Spekrijse, & Roelfsema, 2006; Roelfsema, Lamme, & Spekrijse, 1998).

Attending to an object also has implications for the spatial locations occupied by the object, suggesting a basis for interactions between spatial and object representations. Many recent studies have documented simultaneous object- and space-based effects in the same paradigm using two-dimensional (Egly, Driver, & Rafal, 1994; Martinez et al., 2006; Soto & Blanco, 2004) and three-dimensional displays (Atchley & Kramer, 2001; Robertson & Kim, 1999), and facilitated processing (Davis, Driver, Pavani, & Shepherd, 2000; Matsukura & Vecera, 2006; Vecera & Farah, 1994; Weber, Kramer, & Miller, 1997) and enhanced cortical activation (Müller & Kleinschmidt, 2003) are observed for locations within the boundaries of the selected object. Inhibition of return can also evidence object and space-based components simultaneously (Leek, Repp, & Tipper, 2003; Tipper et al., 1994). By virtue of the object's presence, spatial regions of the visual

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This work was supported by National Institute of Mental Health Grant 54246 to Marlene Behrmann and by National Institute of Mental Health Training Grants to Brian MacWhinney and Lynn Reder. We thank Patricia Carpenter and Roberta Klatzky, who both provided invaluable advice and comments.

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field within the object's boundaries can accrue preferential benefit (e.g., Kim & Cave, 1995, 2001; Kramer, Weber, & Watson, 1997).

Previous work has attempted to account for these space and object interactions within the biased competition framework by proposing that competition takes place within object-selective regions of cortex wherein one object wins out over another by virtue of its bottom-up salience or a top-down bias favoring one object (e.g., an endogenous cue; Vecera & Behrmann, 2001). The consequence of being the victor is that various features of the winning object come to be preferentially represented, giving rise to the behavioral advantage for that object over others in the visual field. Given the bidirectional feedback from object-selective cortical regions, a biasing signal is propagated from the winning object representation to earlier spatial regions of visual cortex. Such feedback enables those neurons with receptive fields lying within the object also to gain a competitive advantage (Deco & Lee, 2002; Kramer et al., 1997; Vecera, 1997).

A prediction that emerges naturally from this feedback account is that information appearing in the surround of the cued object would also be positively facilitated along with information that falls within the boundaries of the object. One might also expect the facilitation in the surround to be dependent on distance from the cue, as was observed in spatial cuing paradigms. However, once feedback from higher order areas activates neurons in lower level cortex, by virtue of the local spatially dependent interactions, these neurons would, themselves, generate spatial gradients of activation that would not strictly obey the boundaries of the selected object. Thus, facilitation should be observed for information in the cued location, in locations occupied by the body of the object, and in locations in the surround, with this last exterior gradient being contingent on spatial distance from the body of the object. This prediction implies that the function of OBA is not solely to select out an individual object for further processing but also to create a scenewide representation defined by the selected object.

In this article, we present a series of experiments designed to examine the nature and extent of attentional facilitation in the surround of an attended object. In these experiments, the speed of target detection is measured in displays in which targets are spatially equidistant from a cued location but vary in distance relative to the position of the attended object. In Experiments 1a and 1b, we confirm that a target nearer to the body of the object is detected faster than a target that is farther away, even though their absolute spatial distance from the cued location is equivalent. In Experiment 2, we confirm that the object's center of mass influences the exterior gradient by systematically probing multiple target locations, all of which are equidistant from the cue but vary in distance from the center of mass of the object. In Experiment 3, we manipulate the cued object's center of mass by changing the shape of the object while absolute target locations are held constant; the results also reveal an advantage for targets that are closer to the object's center of mass compared with those located farther away. Taken together, these findings provide strong evidence that object- and space-based attention interact to create a scenewide pattern of facilitation based on distance from the attended object.

Experiment 1a

The goal of this first experiment was to demonstrate that targets both in the surround of and within an attended object are facilitated

by OBA. Moreover, this experiment was designed to confirm that, of two targets in the surround, both equidistant from a cued location, the target closer to the body of the attended object is detected faster than one farther away.

Method

Participants. All 46 participants gave informed consent and received either payment (\$7) or course credit, in compliance with approval of the Institutional Review Board of Carnegie Mellon University. Participants had normal or corrected-to-normal vision by self-report. Ten of these participants were excluded from the final analyses for having high false alarm rates.

Stimulus, apparatus, and procedure. Participants were seated in a dimly lit room approximately 48 cm from a 19-in. Dell M992 flat CRT monitor. Stimulus presentation and reaction time (RT) collection were done using the E-Prime (available from <http://www.pstnet.com>) software package running on a Dell Dimension 8200.

Each trial began with a 1-s stimulus display, which contained a single object and a fixation cross in the center of the screen. The background of this display was white (Commission Internationale de l'Eclairage [CIE]: $x = .254$; $y = .325$) with a luminance of 57 cd/m^2 . The object was gray (CIE: $x = .256$; $y = .316$) with a luminance of 12 cd/m^2 . These luminance and CIE values were constant throughout the experiments. Following the stimulus display, a black cue overlying part of the contour of the object appeared for 100 ms. Another 100-ms presentation of the stimulus display followed, and then the target (a fully blackened circle) appeared simultaneously with the stimulus display for a further 1 s. Participants had 1,500 ms from the target onset to respond via a key press. Their response triggered the onset of a 500-ms intertrial interval in which there was no stimulus, followed by the beginning of the next trial. In the absence of a response, the intertrial interval began automatically after 1,500 ms. To ensure selective responding, we included catch trials in which the target did not appear. Participants were forcefully instructed to maintain fixation throughout every trial and to respond as quickly as possible to the target while minimizing false alarms on catch trials.

Design. The stimulus display contained a barbell, a disjoint barbell, or a pair of circles, oriented vertically or horizontally (see Figure 1), constituting a 3×2 between-subjects design. The cue involved the darkening of one end of the barbell or one circle. Because the stimuli could appear above or below or to the right or left of fixation, there were four possible cue locations (upper right/left and lower right/left), all positioned 4.1° from fixation, constituting the vertices of a square. In this arrangement, the absolute physical location of cues and targets are held constant across orientation and stimulus display. The target could appear either at the cued location (*valid*) or in one of three invalid locations (*within-object*, *near-object*, *far-object*), all equidistant from the cued location (5.8°), and probed with equal probability. Note that the within-object location refers to the uncued circle for the disjoint and circle displays. The near- and far-object targets were positioned 7.8° from fixation and are referred to as exterior targets.

Participants completed 12 blocks of 100 trials, containing 16 catch (4 per cue location), 60 valid (15 per cue location), and 24 invalid (8 per cue location) trials. A break was given between blocks. Blocks in which a participant made four or more false alarms to catch trials were

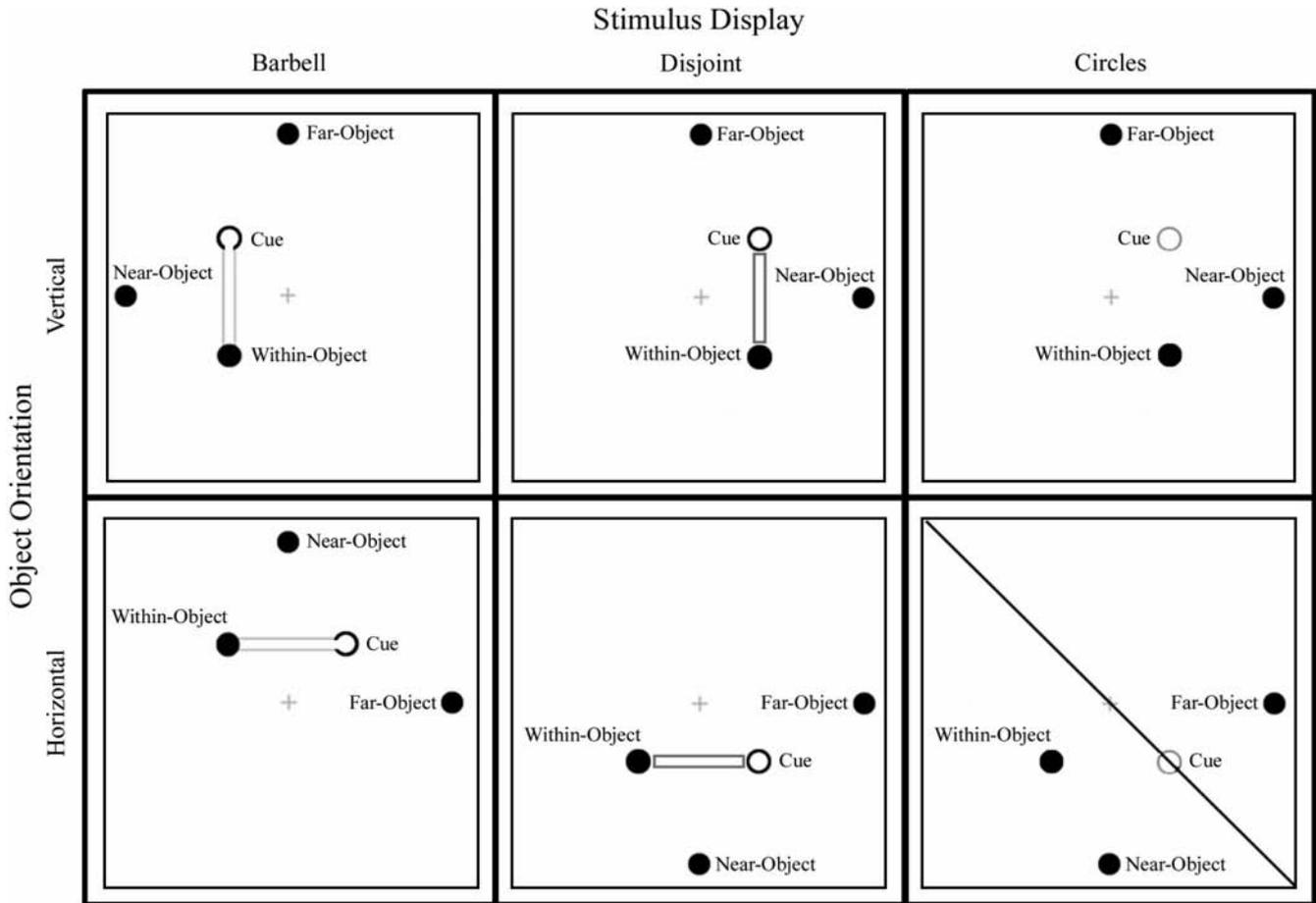


Figure 1. Displays used in Experiment 1a. All targets and cues within objects appeared 4.1° of visual angle from fixation. Both exterior targets appeared 7.8° away from fixation. All invalid targets appeared 5.8° away from the cued location. Note that only the cued location and not the cue itself is pictured in the circles displays in order to give a clearer depiction of those stimuli. The appearance of the cued circle in those displays was identical to that pictured in the disjoint condition. The diagonal line in the bottom right cell indicates the criterion used for the exclusion of eye movements in Experiment 1b. Any eye movement below that line was excluded, as those points are closer to the near- than to the far-object target.

excluded from further analysis. If four or more blocks were excluded, all of the participant's data ($n = 10$) were excluded; in the remaining 36 participants ($n = 6$ per between-subject cell), the mean number of blocks considered was 10. The excluded participants averaged 54 false alarms ($\sim 28\%$). The included participants rarely failed to respond to targets ($< 0.5\%$).

In the barbell display, as predicted by OBA accounts, we expected to observe fastest detection of the valid probe followed by the invalid but within-object probe. Although the exterior targets were equidistant from the cue, the further prediction was that because of its smaller average distance from the barbell, the near-object target would be detected faster than the far-object target, reflecting the dependency of the exterior gradient on distance from the body of the object. Note that the near- and far-object targets switched between orientation conditions, controlling for baseline differences in RT to any one location (Figure 1).

If the facilitation of the near-object target is contingent on cuing a unified object, then, on our account, the difference in RT be-

tween the near- and far-object targets should not be observed in either the disjoint or the circles condition. In both of these displays we should still observe the fastest RT to the valid target. The target appearing in the uncued circle (within-object) might also be detected faster than either of the exterior targets owing to its smaller distance from fixation and its overlap with a stable preexisting object in the display. This advantage for the within-object target should also be stronger in the disjoint than in the circles condition owing to the increased grouping afforded by the presence of the bar lying between the two circles. But the important prediction is that no difference between the near and far object should be obtained in either the circles or the disjoint condition.

Results and Discussion

We first examined the effects of cue location and object orientation on performance. Participant RT medians were analyzed in a four-way mixed-design analysis of variance (ANOVA) with target

location (valid, within-object, near-object, far-object) and cue location (upper left, upper right, lower left, lower right) as within-subject factors and object orientation (vertical, horizontal) and stimulus display (barbell, disjoint, circles) as between-subject factors. No main effects or interactions were observed with either cue location or object orientation ($p > .10$), and the remaining analyses are collapsed across these factors. RTs differed as a function of target location, $F(3, 99) = 106.09, p < .001, \eta_p^2 = .77$, and of stimulus display, $F(2, 33) = 5.40, p < .01, \eta_p^2 = .25$. Of note, these two factors interacted significantly, $F(6, 99) = 8.99, p < .001, \eta_p^2 = .36$.

In all three stimulus displays, RTs increased monotonically across the four levels of target location, as predicted (Figure 2a). To take baseline RT into account, we computed difference scores by subtracting the median valid RT from each of the other target location medians within each participant (Figure 2b) and entered these scores into a two-way ANOVA with target location (within-object, near-object, far-object) as a within-subject factor and stimulus display (barbell, disjoint, circles) as a between-subjects factor. Consistent with the predictions, the patterns of RTs for the three target locations differed across stimulus displays, resulting in a significant interaction between these factors, $F(4, 66) = 5.04, p < .01, \eta_p^2 = .25$. As revealed by planned paired t tests, the difference score of within-object target location was less for the barbell than for the circles display, $t(11) = 2.22, p < .10$, reflecting a weaker within-object benefit in the circles condition, as expected. The difference score for the within-object target location did not vary

significantly between the barbell and disjoint conditions, $t(11) = 1.38, p > .10$.

The differences between near- and far-object targets fell in the expected pattern across the three stimulus displays (circles = 0.06 ms, disjoint = 2.67 ms, barbell = 10.21 ms). To test whether these differences were significant, we entered difference scores into a two-way ANOVA with target location (near-object, far-object) as a within-subject factor and stimulus display (barbell, disjoint, circles) as a between-subjects factor. This ANOVA revealed a significant interaction between stimulus display and target location, $F(2, 38) = 4.04, p < .05, \eta_p^2 = .16$. The difference between the near- and far-object target difference scores was larger in the barbell condition than in the other stimulus displays, leading to significant interactions between both the barbell and disjoint conditions, $F(1, 22) = 4.24, p < .05, \eta_p^2 = .16$, and the barbell and circles conditions, $F(1, 22) = 5.57, p < .05, \eta_p^2 = .20$. No significant interaction between the exterior target difference scores was observed between the circles and disjoint conditions ($p > .10$). These results support the hypothesis that the behavioral facilitation of exterior locations depends on their proximity not just to the cue but to the entire body of the unified, cued object.

It is interesting but unsurprising to note that the organization of the disjoint object was sufficient to bring about some within-object facilitation, relative to the circles condition, but not to affect RTs to the exterior targets. Finding OBA in a stimulus of this type is consistent with previous results showing object-based facilitation in conditions where stimuli are well grouped by Gestalt principles (Behrmann et al., 1998; Behrmann, Zemel, & Mozer, 2000; Matsuoka & Vecera, 2006). The pattern of results in the disjoint condition suggests that RTs to targets in the surround may be a more stringent measure of the objecthood of a stimulus than traditional OBA. Within-object facilitation may still be evident when components of an image are organized in some way, but this perceptual organization may not be sufficiently strong to activate object representations to the extent that they can then feed back and influence the facilitation of the surround.

Experiment 1b

The results of Experiment 1a confirmed that items in the spatial surround of an attended object are perceptually enhanced and that their distance from the cued object is critical in determining the strength of this facilitation. We have suggested that this effect on the surround is a direct consequence of OBA. Previous research, however, has demonstrated that eye movements are often directed to the center of objects (Vishwanath, Kowler, & Feldman, 2000) and even to the center of clusters of random dots (Melcher & Kowler, 1999). Rather than the pattern of facilitation observed in Experiment 1a being a product of attentional selection, then, a possible alternative explanation is that eye movements to the center of the presented object produced the effect.

It is extremely unlikely, however, that eye movements drove the differences in RTs to the exterior targets. First, there was a significant difference in the patterns of RTs to the exterior targets in the barbell and disjoint conditions. Because the disjoint object was grouped to some extent, occupied the same location, and had the same probability of being cued and probed as the barbell, it should have been as capable of drawing eye movements as the barbell. Recalling the pattern of differences in RT between the near- and

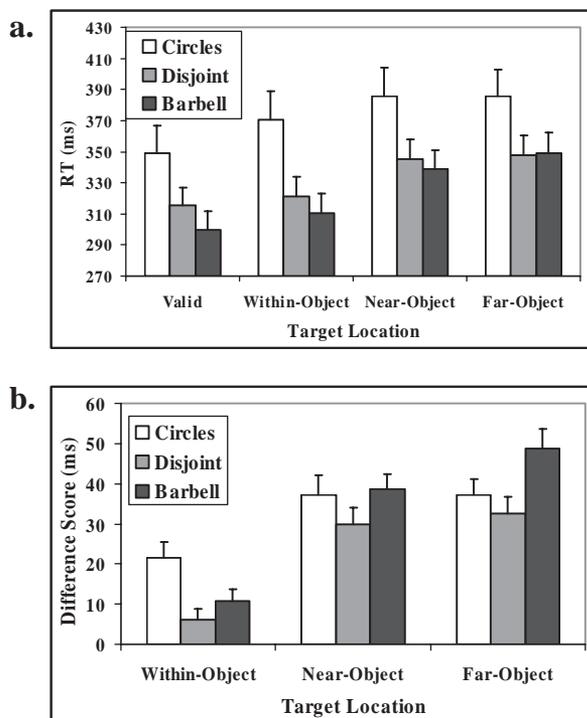


Figure 2. (a) Mean reaction times (RTs) for the levels of target location across the stimulus displays in Experiment 1a. Error bars represent the between-subjects standard error. (b) Mean difference scores across the stimulus displays in Experiment 1a. Error bars represent the between-subjects standard error.

far-object targets (circles = 0.06 ms, disjoint = 2.67 ms, barbell = 10.21 ms), the disjoint and circles objects would need to be 4 and 163 times less likely to draw eye movements, respectively, than the barbell if eye movements were responsible for the observed differences in RT. Given the identical task demands and probe and cue probabilities, this is extremely unlikely. Although the eye movement explanation is unlikely from a logical standpoint, in Experiment 1b we replicated the results of the barbell condition while tracking the eye movements of the participants so as to rule out definitively eye movements as the source of the effects in the surround. Specifically, we predicted that the pattern of RTs to the exterior targets would be the same as in the barbell condition of Experiment 1a while we ensured participants' eyes remain fixated, thereby confirming that the effect could not be attributable to eye movements.

Method

Participants. All 5 participants gave informed consent and received either payment (\$10) or course credit, in compliance with approval of the Institutional Review Board of Carnegie Mellon University. Participants had normal or corrected-to-normal vision by self-report.

Stimulus, apparatus, and procedure. Participants were seated in front of a Dell Inspiron 8200 laptop computer with 15.4-in. screen and were positioned in a chin rest. The sizes of all stimuli were altered to ensure they subtended the same degrees of visual angle as in Experiment 1a.

At the beginning of each block, participants fixated a series of dots occupying the locations of fixation and all possible target locations to allow for calibration of the fixation data. Fixations were sampled at 60 Hz in x and y dimensions throughout the experiment using an Iscan Model RK-726 video-based eye tracker. The eye movement data were collected and then analyzed offline for any breaks from fixation.

Design. The paradigm was identical to the vertical barbell condition in Experiment 1a, save that it contained only 11 blocks. Instructions to participants were identical to those provided in Experiment 1a. There was a loss in signal from the eye tracker in approximately 10% of the trials. These trials and those in which a participant made any movement greater than 2° from fixation during the 700 ms prior to the onset of the target were excluded from analysis ($\sim 50\%$). This criterion is very conservative but ensured that eye movements would not contaminate the acquired data. Blocks of trials were excluded from the final analysis on the same basis as in Experiment 1a. The mean number of blocks considered from each participant was 10.2.

Results and Discussion

Participant RT medians from the eye-tracking condition in Experiment 1b and the vertical barbell participants from Experiment 1a were entered into a three-way mixed-design ANOVA with target location (valid, within-object, near-object, far-object) and cue location (upper left, upper right, lower left, lower right) as within-subject factors and tracking condition (vertical barbell, vertical barbell with eye tracking) as between-subjects factors. No main effect of tracking condition or interactions between it and any other factor were observed ($p > .10$). A highly significant main

effect of target location was observed, $F(3, 27) = 19.41, p < .001, \eta_p^2 = .65$. The observed difference between the RTs to the near- and far-object targets was even numerically, albeit not significantly, larger than the difference observed in the vertical barbell condition (vertical barbell = 10.21 ms; vertical barbell with eye tracking = 12.10 ms).

As an even stronger test of whether eye movements were driving the RTs to the exterior targets, we reanalyzed the data, excluding only those trials in which eye movements were made that would support the predictions. Given the hypothesis that the near-object target should be detected more quickly than the far-object target, we reasoned that trials in which participants fixated at points closer to the near- than to the far-object target needed to be excluded. This criterion was used to exclude trials in which there was an eye movement of more than 2° from fixation to those points during the 700 ms prior to the onset of the target and trials in which the eye tracker lost signal ($\sim 30\%$ of trials). Eye movements toward the half of the display that would work against the hypothesis were allowed (see Figure 1, bottom right, for criterion). This provided the strongest possible test of whether eye movements are driving the RTs.

Again, even under these conditions, we observed no significant main effects or interactions involving tracking condition ($p > .10$) and a nearly identical difference between the exterior targets (vertical barbell = 10.21 ms; vertical barbell with eye tracking = 11.01 ms). These results verify that the enhanced facilitation to the near-object target observed in the barbell condition is not due to eye movements executed in the direction of the attended object.

Taken together, the results of Experiments 1a and 1b clearly demonstrate that a cued unified object plays a critical role in defining the exterior spatial gradient that surrounds an attended object. The immediate question, then, concerns what aspect of the object is central to this process.

Experiment 2

The results of Experiments 1a and 1b suggest that the exterior gradient is contingent on distance from the object's center of mass. The center of mass has previously been shown to cause a shift in the allocation of attention within an object, causing a systematic bias in line-bisection tasks (Shuren, Jacobs, & Heilman, 1997). More recent studies have also found facilitation for information occurring at the center of mass of moving lines (Alvarez & Scholl, 2005). The center of mass corresponds with the average location of all of the points within the bounds of the attended object. On our object-based account, all of these points should be activated and should contribute to the overall form of the exterior gradient, making it a likely candidate in terms of our proposed competitive mechanism. In Experiment 2, we examined whether the distance from the object's center of mass per se defines the exterior gradient. This was achieved by quantifying the parameters of the spatial gradient through the inclusion of multiple exterior targets, all of which were equidistant from the cue but varied systematically in distance from the object's center of mass. We deliberately avoided probing or cuing the center of mass so as to keep the center of mass entirely task irrelevant, allowing us to rule out, as an explanation for the findings, the possibility that participants directly attended to the center of mass in this experiment.

Method

Participants and procedure. A group of 22 participants completed this experiment. The apparatus and procedure were identical to those of Experiment 1a unless noted otherwise in the *Design* section. Seven participants were excluded from the final analyses for having high false alarm rates or extremely long RTs.

Design. The stimulus display contained only a single barbell, aligned on the vertical midline, extending either upward or downward from fixation (see Figure 3). The cue involved the darkening of the end of the barbell that circumscribed the fixation cross. The target (identical to the target in Experiments 1a and 1b) could appear in the same location as the cue (valid) or in one of 12 invalid locations (one of which fell within the cued barbell) arranged in a clock face, equidistant (5.8°) from the cue and fixation but with varying distances from the object center (Figure 3).

Each participant completed 10 blocks of 128 trials, containing 12 catch (6 per object orientation), 68 valid (34 per object orientation), and 48 invalid (4 per location) trials. Blocks in which a participant made three or more false alarms to catch trials were excluded from further analysis. Five of the 22 participants were excluded because two or more blocks of their data failed the inclusion criterion.¹ The excluded participants averaged 45 false alarms (~38%) over the course of the experiment. One additional participant was excluded because his average raw RT exceeded five standard deviations from the group mean (group mean RT = 329 ms; excluded participant mean RT = 629 ms). For the remaining 16 participants, the mean number of blocks considered was 9.4.

Results and Discussion

First, participant RT medians were analyzed in a two-way ANOVA, with object orientation (upward, downward) and target location (valid, within object, 180°) as within-subject factors, showed a main effect of target location, $F(2, 30) = 13.70$, $p < .001$, $\eta_p^2 = .50$, and no main effect or interaction involving object orientation. Planned paired t tests between the three levels of target location verified that they fell in the expected order, with fastest RTs to valid, within-object, and 180° targets in that order (valid vs.

within-object: $t(14) = 3.11$, $p < .01$; within-object vs. 180° : $t(14) = 2.25$, $p < .05$).

In the analysis of primary interest, RT medians were analyzed in a three-way repeated measures ANOVA with target location (30° , 60° , 90° , 120° , 150°), hemifield (left, right), and object orientation (upward, downward) as within-subject factors. This ANOVA also revealed no significant main effects or interactions involving object orientation or hemifield ($p > .05$), and all remaining analyses are collapsed over these two factors.

To account for any individual baseline differences, the median valid RT ($M = 340$ ms) for each participant was subtracted from their median RT for each target location, yielding difference scores (see Figure 4a). An ANOVA on the difference scores for the six exterior target locations with target location (30° , 60° , 90° , 120° , 150° , 180°) as a within-subject factor revealed a main effect of target location, $F(5, 70) = 2.47$, $p < .05$, $\eta_p^2 = .16$, and a highly significant linear trend among the target locations in the expected order, $F(1, 14) = 19.46$, $p < .001$, $\eta_p^2 = .58$. This result supported a monotonic increase in RTs to the exterior targets as the distance from the object's center of mass increased. Note that the location of the center of mass was taken as the exact center of the object, halfway between the circular ends of the barbell. A regression performed on the RT data against the distances from the six exterior target locations to the center of mass of the object yielded an R^2 of .98 and a 1.99-ms cost in RT per degree of visual angle from the center of mass (Figure 4b), providing a quantification of the exterior gradient under these particular experimental conditions.

The major result from this experiment is that even when the absolute distance from the cue is held constant, RT to detect the presence of a target varies as a linear function of the distance from the center of mass of the cued object. These findings are consistent with the notion that when an object is cued and selectively attended, an exterior spatial gradient forms, such that behavioral facilitation in the surround is determined by proximity to the center of mass. This experiment also establishes that the effect is not specific to the small set of locations probed in Experiments 1a and 1b.

Experiment 3

The results of Experiment 2 provide strong evidence for the claim that the center of mass of the attended object plays a critical role in determining the form of the exterior spatial gradient. In the final experiment, we confirm this finding by holding the location of the exterior targets constant and manipulating the center of mass by changing the object's shape.

Method

Participants and procedure. A total of 37 participants completed this experiment. Of these participants, 6 completed the experiment while their eye movements were tracked. The eye-tracking procedure and paradigm were identical to those of Ex

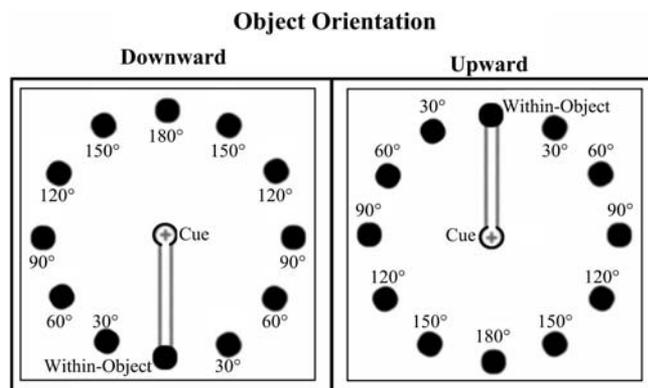


Figure 3. Displays used in Experiment 2. The cue always appeared at fixation, and all targets appeared 5.8° away from the cued location. The numbers above the exterior targets indicate their degree of rotation away from the midline axis defined by the object.

¹ Note that the exclusion criteria from Experiment 1 were revised slightly to compensate for the smaller number of blocks and catch trials and the larger number of conditions in Experiment 2. These criteria ensured there would be a sufficient number of trials in each condition of interest.

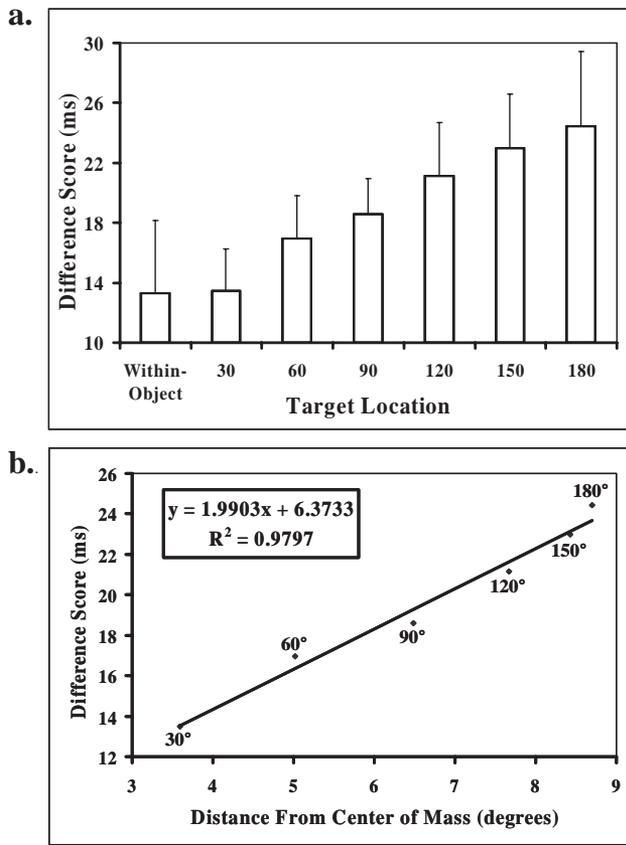


Figure 4. (a) Mean difference scores for all target locations in Experiment 2. Error bars represent the between-subjects standard error. (b) Mean difference scores for these locations plotted against their actual distance in degrees of visual angle from the cued object's center of mass. Error bars represent the between-subjects standard error.

periment 1b unless otherwise noted. Of the 31 participants whose eye movements were not tracked, 13 were excluded from the final analyses for having a high number of false alarms to catch trials and/or extremely long RTs.

Design. A cross was used for the cued object, as this allowed us to manipulate the object's center of mass by varying the location of the horizontal bar of the cross (near the top, middle, or bottom of the vertical bar). This manipulation controlled the proximity of the object's center of mass to two exterior targets whose positions remained constant and equidistant from the cue. The cue involved darkening the top or bottom end of the cross, which could appear to the left or right of fixation, creating the same four possible cue locations as in Experiment 1. The target (a black square) could appear in the same four locations as in Experiment 1 (valid, within-object, near-object, far-object). These manipulations constituted a within-subject design of the form: cue location (4) \times bar position (3) \times target location (4).

Each participant completed 10 blocks of 132 trials, containing 12 catch, 72 valid, and 48 invalid trials. Each type of invalid trial occurred with equal frequency in each block. Blocks in which participants made three or more catch trial errors were excluded from further analyses. Eleven participants were excluded because two or more blocks of their data failed the inclusion criteria. These participants made an average of 41 false alarms (~34%) over the course of the experiment. An additional 2 participants were excluded because their RTs were more than 3.5 standard deviations above the mean (mean included RT = 369 ms; mean excluded RT = 585 ms). No eye-tracking participants were excluded on either of these bases. In the remaining eye-tracking ($n = 6$) and non-eye-tracking ($n = 18$) participants, the mean number of blocks considered was 9.0 and 9.3.

There was a loss in signal from the eye tracker in approximately 10% of the data. These trials and those in which a participant made any movement greater than 2° from fixation during the 700 ms prior to the onset of the target were excluded from analysis (~45%). This criterion is very conservative but ensured that eye movements would not contaminate the acquired data.

If the exterior gradient is warped as a function of proximity to the center of mass of the object, we would expect an interaction between target location and bar position. Figure 5 shows the distances of the exterior targets (equidistant from cue) from the three different objects' centers of mass, which were calculated by extracting the average coordinates of locus of points occupied by the object. RTs to the near-object target should be roughly equiv-

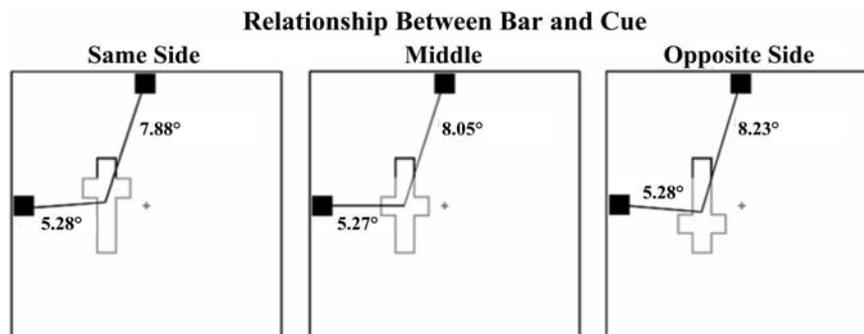


Figure 5. Displays used in Experiment 3. The locations of all cues and targets in this experiment were identical to those in Experiments 1a and 1b. The black lines in the display were not presented to participants and are meant to show the variation in distance from the center of mass of the object to the near and far object targets across the three possible bar locations.

alent in all three bar conditions. RTs to the far-object target should be fastest when the bar and cue are on the same side, followed by when the bar is in the middle, and should be slowest when the bar appears on the side opposite the cue. There should also be no difference between the eye-tracking and non-eye-tracking participants, ruling out eye movement as the source of the RT difference between the near- and far-object targets.

Results and Discussion

Participant RT means were analyzed in a four-way repeated measures ANOVA with cue location (upper left, upper right, lower left, lower right), bar location (same side, middle, opposite side), and target location (valid, within-object, near-object, far-object) as within-subject factors and tracking condition (eye-tracking, non-eye-tracking) as a between-subjects factor. A significant main effect of target location, $F(3, 72) = 71.87, p < .001, \eta_p^2 = .76$, and an interaction between bar location and target location, $F(6, 144) = 2.41, p < .05, \eta_p^2 = .10$, were observed. No main effects or interactions involving either cue location or tracking condition were observed ($p > .10$), and thus the remaining analyses are collapsed across this factor (see Figure 6a).

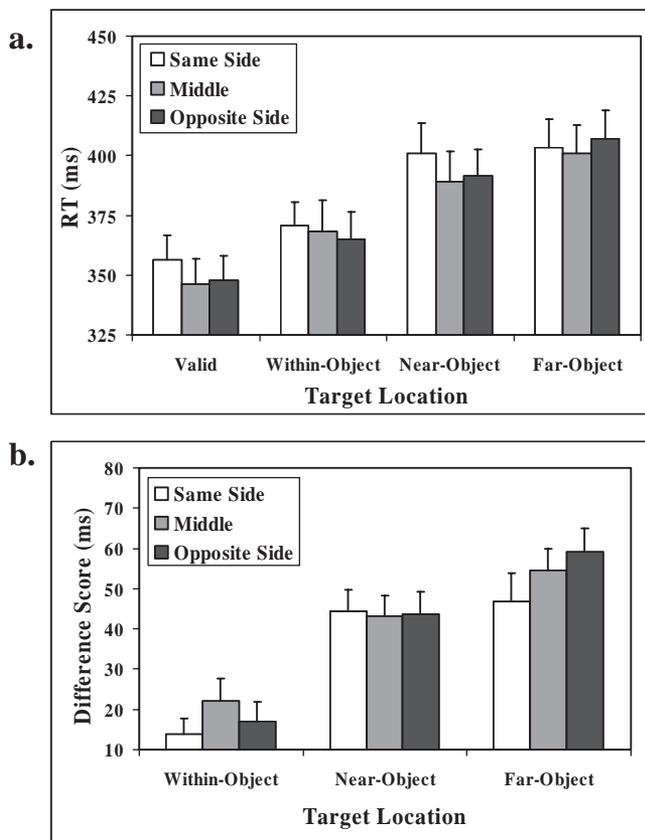


Figure 6. (a) Mean reaction times (RTs) for the levels of target location for the three bar locations in Experiment 3. Error bars represent the between-subjects standard error. (b) Mean difference scores for the levels of target location for the three bar locations. Error bars represent the between-subjects standard error.

As before, difference scores were derived and analyzed in a two-way repeated measures ANOVA with bar location (same side as cue, middle, opposite side) and target location (within-object, near-object, far-object) as within-subject factors. A significant main effect of target location, $F(2, 48) = 28.69, p < .001, \eta_p^2 = .56$, and a significant interaction between bar location and target location, $F(4, 96) = 2.71, p < .05, \eta_p^2 = .11$, were obtained. The difference between the difference scores for the near- and far-object targets was larger for the opposite-side than for the same-side bar location, $F(1, 24) = 5.26, p < .05, \eta_p^2 = .19$, following the expected pattern (same side = 2.5 ms; middle = 11.45 ms; opposite side = 15.43 ms; Figure 6b). For the middle bar location, this difference fell between the difference scores of the other two conditions, and the effect was almost exactly the same size as observed in the vertical barbell condition of Experiment 1 (vertical barbell = 10.21 ms; middle bar location = 11.45 ms).

As predicted, the difference in RT between the exterior target locations across the bar locations was primarily driven by differences in RT to the far-object target. Target detection in the near-object position was not affected by bar location, $F(2, 48) = 0.03, p = .97, \eta_p^2 < .01, MSE = 268.54$, which was predicted on the basis of the negligible difference in distance from the center of mass across these conditions. At the same time, RT for the far-object target varied significantly across the different bar locations, $F(2, 48) = 4.90, p < .05, \eta_p^2 = .18$, with faster RTs for same-side than for opposite-side bar locations, $F(1, 24) = 11.11, p < .01, \eta_p^2 = .33$.

This experiment further supports the hypothesis that the center of mass of a cued object affects the exterior gradient of attention. This finding is particularly compelling because the exterior probed targets were both equidistant from the cue and constant in absolute retinal location, but nevertheless, the speed of target detection varied in relation to the shape (and hence center of mass) of the object.

General Discussion

Much of the recent research in the domain of visual attention has been concerned with characterizing the unit of attentional selection, focusing in particular on whether either or both spatial location and objects can be preferentially attended and selected. A major conclusion of this research has been that visual attention can be directed not only to spatial locations but also to objects. The current work went beyond this and examined the consequences of OBA for information that falls outside of the boundaries of an attended object. The essential question is whether, once an object is attended and perceptually enhanced, information in the surround also accrues some systematic benefit.

The major result of the series of experiments reported in this article is that not only does OBA facilitate processing at locations

²One possible confound in this experiment is that the cross-shaped stimulus acted as an arrow, endogenously cuing participants to attend toward the end of the object nearest the horizontal bar. However, were this the case, there should have been larger shifts in RT to the exterior targets than were observed. In fact, were attention focused on a point beyond the end of the arrow, the far-object target should have been faster than the near-object target. This is clearly not the pattern obtained in this experiment.

within the bounds of an object, as expected, but information that appears in locations exterior to the object is also simultaneously facilitated. More specifically, information appearing in locations in closer proximity to the cued object enjoys an advantage in the speed of target detection compared with information in more distant locations. Furthermore, the gradient by which attentional facilitation falls off is determined by the center of mass of the object; when two locations are probed, both of which are spatially equidistant from the cued position, the location that is closer to the center of mass of the cued object benefits to a greater degree. Of note, we have also demonstrated that the facilitation afforded to the targets in the surround of the object is not a result of eye movements. When participants' eye movements were tracked and trials on which the eyes moved from fixation removed, the same facilitation of the near- over far-object target location was obtained. Finally, we have been able to quantify the extent of this attentional facilitation, revealing a highly linear 1.99-ms increase in RT for every degree of visual angle away from the object's center of mass. Taken together, these results demonstrate that object and spatial representations interact to determine perceptual facilitation throughout a visual scene.

Our finding of a linear relationship between distance from the center of mass and degree of attentional facilitation seems at odds with other recent research demonstrating a nonlinear Mexican-hat profile of spatial attention (Müller, Mollenhauer, Rösler, & Kleinschmidt, 2005). However, the Müller paradigm investigated the suppression of spatially deterministic distracting flankers, whereas our task involves probabilistic target detection with a precue and no suppression component. It is possible that the Mexican-hat profile is specific to the mechanisms by which distracting information is suppressed, whereas our linear profile more closely approximates the default pattern of facilitation in scenes without distracting information. More research is needed to understand the precise way these two measures of attention relate.

The finding that the center of the object plays a crucial role in mediating the processing of targets in the surround is consistent with results implicating the center of mass or gravity as critical (Vishwanath & Kowler, 2003; Vishwanath et al., 2000) and with theoretical frameworks in which the midline axis or midpoint of the object representation has a privileged status (Blum, 1973; Kovacs, Fehér, & Julesz, 1998). Recent findings have also shown attentional facilitation for the center of multiple moving lines during an object-tracking task (Alvarez & Scholl, 2005). In this last study, at random times, probes appeared at the center or near the endpoints of any one of multiple lines, all of which were rotating simultaneously. Even when the observers knew the probes were more likely to appear near the line endpoints, a relative facilitation was still observed at the center of the line, attesting to the robustness of the object center in attentional selection.

Another possibility is that it is the average distance from the object contour that is the determining factor rather than the distance from the center of mass of the object. One previous study has shown that distance from the object contour was a key factor in distractor suppression even when distance from the center of mass was held constant (Eriksen, Pan, & Botella, 1993). However, in this task, the contours of the object were directly behaviorally relevant, as they indicated whether a response was required on any particular trial, making such a finding unsurprising. Also, in most natural stimuli, the internal details of an object are directly rele-

vant, making the center of mass a more reasonable measure of the distribution of facilitation throughout an object. In the set of studies presented here, though the object contours are not behaviorally relevant, distance from the center of mass and average distance from the object contour are confounded.

We have suggested that the key mechanism by which the targets in the exterior locations are enhanced is one in which top-down object information feeds back to lower levels of the visual system. Under this account, feedback from object-level representations provides support for the locations within the attended object. These locations, in turn, give rise to spatial gradients, causing the overall pattern of facilitation in the surround to correspond to a symmetrical spatial gradient around the center of mass of the object. According to the simple computation we are proposing, a complex asymmetrical object may give rise to a center of mass that falls outside its boundaries.

In situations where the top-down object information is a hindrance to the task or where bottom-up cues are more salient than the object-level structure, both OBA and the impact of center of mass on the exterior gradient should be greatly reduced. Thus, our account predicts that any effect of OBA, including the center of mass effects demonstrated in these experiments, should be subject to the broader constraints of the experimental context. Previous research has demonstrated that probability manipulations are capable of modulating spatial and object-based attentional effects (Fournier & Shorter, 2001; Shomstein & Yantis, 2002, 2004). If the far-object target were much more probable than the near-object target, the RT advantage of the near-object target should be eliminated. Similarly, if the likelihood of the within-object target is reduced such that it is far less likely than the exterior targets, we expect to both eliminate OBA and observe a reduction in the advantage of the near-object target. We hope to test these predictions in future research.

Specifying the neural mechanism underlying these findings will require further study, but the data are consistent with the dynamic modulation of early visual areas by feedback from object selective regions. These feedback signals could create both a gain in neural response and an increase in selectivity in early visual areas (Murray & Wojciulik, 2004; Shomstein & Behrmann, 2006), and this would help explain the pattern of early and late visual area activity observed in object-cuing tasks (Arrington, Carr, Mayer, & Rao, 2000; Gustavo & Rolls, 2004; Müller & Kleinschmidt, 2003). Local interactions and overlapping receptive fields could then act to create a spatial gradient like those described above wherein facilitation decreases with increasing distance from the center of mass.

An outstanding question concerns the nature of the object representations that subserve this top-down feedback. Top-down support for the exterior targets might be derived from intermediate level representations depicting the organization of bound oriented line segments obeying Gestalt rules of closure or from higher level object representations, which also support object identification. It is interesting to note that even the minimal objects in our displays are sufficient to bring about the formation of an exterior gradient, attesting to the robustness of the attentional processes at work. We have uncovered at least one constraint on this top-down object-level feedback representation: There must be sufficient activation of an object representation in order to obtain this feedback. In Experiment 1a, in the case of the disjoint barbell, although there

was some facilitation afforded to the invalid but within-object location (the other circle at the end of the disconnected rectangle), this was insufficient to drive an object representation whose activation could feed back down to restructure the spatial gradient. The within-object facilitation observed in the disjoint condition is in keeping with other studies showing that stimuli that can be configured into a well-defined shape often evoke OBA (Behrmann, Zemel, & Mozer, 2000; Matsukura & Vecera, 2006; Vecera & Behrmann, 2001). However, the disjoint barbell does not suffice as a good enough "object" whose activation can lead to a restructuring of space.

Our feedback account might also generalize beyond space and objecthood to other stimulus dimensions, like color. If the attended object is of a particular color, say red, neurons in cortical regions concerned with representing color (e.g., area V4) that are sensitive to the color red might also be activated. This activation will feed back to earlier visual areas, and neurons whose receptive fields overlaid locations in which something red is located will also accrue some competitive advantage, notwithstanding that these locations are not of current interest (for related findings, see Kim & Cave, 2001; Saenz, Bucaras, & Boynton, 2002). This effect is analogous to the advantage that accrues between spatially neighboring stimuli, which may evoke similar responses in retinotopically mapped early visual cortex. Ultimately, in a more complex scene, the overall distribution of attention may depend on the similarity of stimuli across a number of different dimensions, space and color being just two of them (see also Desimone & Duncan, 1995, for similar ideas in a biased competition account). Distributed activation across neighboring representations may also explain why behaviorally irrelevant features of cued objects still evoke neural responses (P. Downing, Liu, & Kanwisher, 2001).

This account is not meant to suggest that all attentional selection and facilitation must be mediated by spatial representations, as suggested by Kramer et al. (1997) or Schendel, Robertson, and Treisman (2001). Rather, according to this account, attentional effects are generated by interactions occurring throughout the perceptual system at every level of representation. Selection and facilitation can occur at any or all of these levels simultaneously. The overall pattern of facilitation is determined by the particular content of the stimuli in the scene and the relative importance of that content for the task, rather than being determined solely by the spatial relationships in the scene. Attentional effects can be observed in changes to the receptive field properties of cells subserving representations of contrast or shape depending on the task demands (Chelazzi, Miller, Duncan, & Desimone, 2001; Reynolds & Chelazzi, 2004). Attention is best thought of as the distributed process by which the perceptual system generates a systematic and unified representation of the stimulus space and task.

One strong prediction of this account is that we should observe direct object-level perceptual facilitation without the need for facilitation of spatially precise representations. In the experiments presented here, the exterior targets occur in the undifferentiated background, where there is no perceptual dimension other than their location to define them. Because their presentation does not implicate any object-level representation per se, their detection is likely subserved mainly by spatial representations. Although the data we have presented suggest that spatial locations are highly relevant even under circumstances where object representations are engaged, it is likely that targets occurring on the body of

attended objects directly perturb spatially invariant object representations, providing an additional mechanism for their detection (Vecera, 1994, 1997). Evidence for this type of spatially invariant attentional facilitation has already been observed in the extensive object-priming literature wherein priming is shown to be largely orientation, position, and size invariant (e.g., Arguin & Leek, 2003; Biederman & Cooper, 1991; Fiser & Biederman, 1995). If OBA leads to the facilitation of a spatially invariant object representation, the presentation of a target on an object might alter that representation. That perturbation could then directly indicate the presence of a target without the need to appeal to spatially precise representations. At the very least, these perturbations could contribute to the process of target detection by providing an additional source of support for the target through feedback.

We have suggested that the competitive dynamics mediating attentional distribution are broad enough to impact space and features such as color. Whether they also extend to properties of object shape remains an open issue, but if so, cuing an object might cause some facilitation in other similar shapes in a visual scene by virtue of their overlapping shape representations. It has already been demonstrated that the resolution of competition between objects can influence the distribution of spatial attention at the locations of the objects (Humphreys & Riddoch, 2003), but whether this is affected by shape or color similarity awaits clarification. If unattended objects that are similar to the attended object also accrue some attentional facilitation, spatial gradients may also form relative to the locations within them. This gives rise to the possibility that the scenewide center of mass may fall somewhere between the facilitated objects in a scene and outside of any particular object. Future work will be required to investigate the effects of this and other interactions between space, objects, and their multiplicity of features on the competitive mechanism subserving attention.

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Received September 9, 2005

Revision received June 24, 2006

Accepted June 26, 2006 ■



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