Where does attention go when it moves?: Spatial properties and locus of the attentional repulsion effect

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Reliable effects of spatial attention on perceptual measures have been well documented, yet little is known about how attention affects perception of space *per se*. The present study examined the effects of involuntary shifts of spatial attention on perceived location using a paradigm developed by S. Suzuki and P. Cavanagh (1997) that produces an attentional repulsion effect (ARE). The ARE refers to the illusory displacement of two vernier lines away from briefly presented cues. In Experiment 1, we show that the magnitude of the ARE depends on cue–target distance, indicating that the effects of attention on perceived location are not uniform across the visual field. Experiments 2 and 3 tested whether repulsion occurs away from cue center of mass or from cue contour. Perceived repulsion always occurred away from the cues' center of mass, regardless of the arrangement of the cue contours relative to the vernier lines. Moreover, the magnitude of the ARE varied with shifts in the position of the cues' center of mass. These experiments suggest that the onset of the cue produces a shift of attention to its center of mass rather than to the salient luminance contours that define it, and that this mechanism underlies the ARE.

Keywords: attentional repulsion effect, attention, location perception, shape and contour

Introduction

It has long been accepted that visual attention can be directed to select regions of space other than the point of fixation and can improve detection and identification of peripheral stimuli. As early as 1894, Hermann von Helmholtz noted that voluntary attention can be dissociated from the point of fixation and that one can identify letters more accurately at attended locations (von Helmholtz, 1894). More recent studies have confirmed this observation, demonstrating that observers respond faster to targets at pre-cued locations, producing reaction time "benefits" at attended locations and "costs" at unattended ones (e.g., Posner, 1980). To explore these aspects of selective attention, much of the literature has since examined the effects of various attentional manipulations on measures of reaction time or accuracy in stimulus identification and detection. However, few studies have investigated the effects of attention on the perception of target location itself. Given the centrality of location to theories of attention and to perception more generally, the present study was designed to examine the relationship between attention and perceived location.

Many theories of selective spatial attention assume that observers have automatic access to at least some location information (e.g., Posner, Snyder, & Davidson, 1980; Treisman & Gelade, 1980). Although a coarse representation of visual space may be extracted outside of awareness, an accurate representation of an object's precise location seems to require it. Several early studies demonstrated that observers make fewer errors in reporting a target's position from a small set of possible locations when it is preceded by an informative cue (Butler, 1980;

Egly & Homa, 1984; Muller & Rabbitt, 1989). More recent studies employing the method of reproduction to obtain precise measures of perceived target location have shown that localization accuracy improves when cues are used to draw attention to the target's location (Adam, Huys, van Loon, Kingma, & Paas, 2000; Tsal & Bareket, 1999). Moreover, the variance in localization responses decreases under conditions of focused attention compared to conditions in which observers' attention is divided between two tasks (Newby & Rock, 2001; Prinzmetal, Amiri, Allen, & Edwards, 1998).

The question of how attention affects perceived stimulus location was further addressed by Suzuki and Cavanagh (1997) who reported systematic distortions in perceived location related to shifts of attention. Specifically, they demonstrated that abrupt onset cues that draw observers' attention produce a repulsion effect in which a target presented at midline appears displaced away from the attended cue. As shown in Figure 1, the authors presented two cue circles in diagonally opposite corners of the display, followed by a vernier stimulus—two vertical lines separated by a gap. Observers judged the lines to be offset in the direction opposite to the two cue circles. For instance, if the circles appeared in the upper left and lower right quadrants of the display, the top line of the
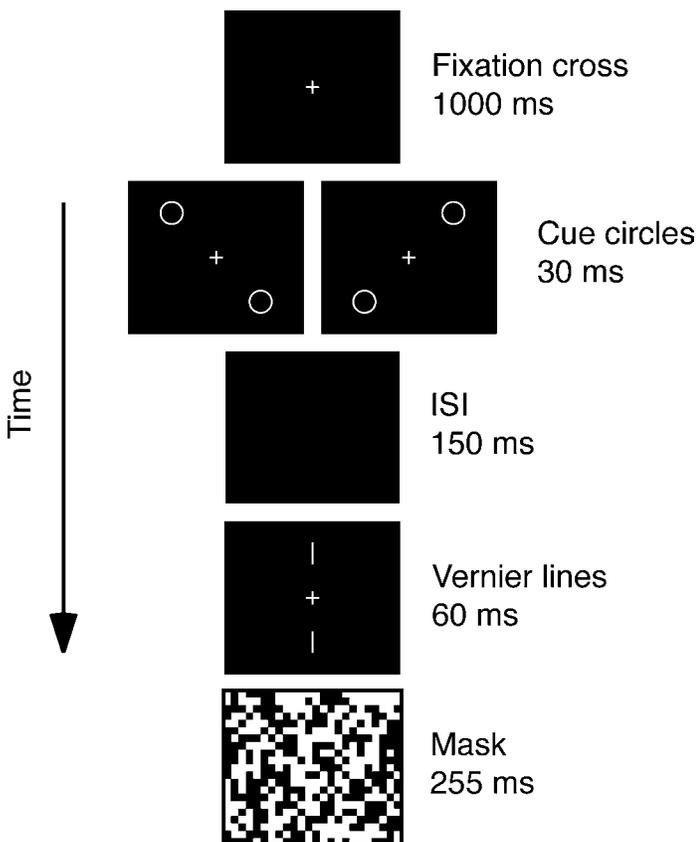

Figure 1. Trial sequence for the attentional repulsion effect (ARE), adapted from Suzuki and Cavanagh (1997). Stimuli are not drawn to scale.

subsequent vernier appeared offset to the right of the bottom line. This distortion is known as the attentional repulsion effect (ARE). Suzuki and Cavanagh propose that the same mechanisms that produce a more accurate encoding of position information at attended locations may result in a cost at minimally attended locations. In this case, involuntary attention to these brief peripheral cues affects the perceived spatial positions of the lines such that they appear displaced away from the cues.

In their experiments, Suzuki and Cavanagh demonstrated that this effect cannot be attributed to apparent motion or to figural aftereffects. Moreover, brief vernier presentation times are necessary for the effect to occur. With sufficiently long exposure durations, observers can shift their attention back toward the center of the display and accurately perceive the locations of the lines. The repulsion effect is also dependent on stimulus onset asynchrony (SOA) between the cues and vernier. The size of the ARE peaks at an SOA of 180–200 ms and is reduced at both short and long SOAs, consistent with the transient effects of peripheral cues on reaction times reported in the cuing literature (e.g., Posner et al., 1980). An additional experiment demonstrated that the ARE could be obtained with voluntary attention to the cues. This effect persisted at longer SOAs, consistent with the longer time course of voluntary over involuntary attention (Nakayama & Mackeben, 1989). The absence of non-attentional explanations, along with evidence that the ARE is sensitive to target duration and SOA, provides strong evidence that the ARE has an attentional basis.

Other research has demonstrated that the attentional repulsion effect can be obtained when observers are required to manually reproduce the target's location (Pratt & Turk-Browne, 2003), when visual cues are replaced by lateralized auditory cues (Arnott & Goodale, 2006) and under a number of other manipulations of exogenous attention, including offset and pop-out cues (Pratt & Arnott, 2008). Together, these findings suggest that while the variance of responses may decrease at an attended location, localization biases outside an attended area may be a necessary cost.

Although the work of Pratt & Arnott (2008) supports the notion that the ARE is related to shifts of attention toward the cued locations, it is not currently known whether attention is drawn to the centers of the circular cues or to the luminance contours that define them. This question is central to understanding the mechanisms underlying attention-based spatial repulsions. If the ARE is purely related to shifts of attention toward a region in space, then the magnitude of the ARE should be constant regardless of the form of the cues, provided that the cues induce shifts of attention to the same location. However, if the ARE is related to both shifts of attention and to the spatial configuration of the display, altering the distances between the contours of the cues and the vernier or changing the size of the cue should systematically alter the size of the ARE.

Given that few studies have examined spatial distortions under different attentional conditions, the findings in the current experiments are related to the broader question of how attention affects perception of space. The present study was designed to examine a number of these properties using the ARE to explore them. Specifically, we examined attentional repulsion in relation to three factors: (1) cue–target distance, (2) changes in the cue contour, and (3) cue center of mass. Together, the results from the three experiments support the notion that shifts of attention to the centers of the cues are responsible for producing the ARE, and that contour–target interactions due to the spatial configuration of the display do not drive the effect. Moreover, our findings suggest that observers have automatic access to the location of an object's center of mass and use this information as a target for subsequent shifts of attention.

Experiment 1

In the original study, Suzuki and Cavanagh (1997) measured the magnitude of the ARE over a range of cue–target distances from 2.1° to 7.7° and found no significant differences within this range. However, the authors also proposed that localized changes in receptive field tuning around the focus of attention may underlie the ARE. If the spatial extent of receptive field modulations is limited around the focus of attention, the amount of perceived repulsion should decrease as the distance between the cue and the target increases. Neurophysiological studies have demonstrated that spatial attention narrows the spatial response profiles of V4 neuronal receptive fields (Moran & Desimone, 1985) and shifts the location of peak activation toward the focus of attention (Connor, Preddie, Gallant, & Van Essen, 1997). In addition, these effects in area MT are greater when attention is focused inside the neuron's receptive field than to an area outside it (Womelsdorf, Anton-Erxleben, Pieper, & Treue, 2006). Thus, attention appears to alter receptive field profiles over a spatially limited range. If changes in receptive field properties are driving the ARE, one might predict a reduction in its size when measured using sufficiently large cue–target distances. This prediction was tested in the first experiment by examining the ARE with a larger range of cue–target distances, from 0.26° to 12.26°, in order to assess whether any dependence exists between the magnitude of the ARE and cue–target distance.

Methods

Participants

Eighteen observers (12 females) participated in the experiment. The mean age of the participants was 20.8 (*SD* = 3.2) with a range of 18 to 29. Sixteen of the participants were undergraduate students at the University of California, Berkeley, and two were trained laboratory members, including one author (F.C.F.). Undergraduates received course credit in exchange for their participation. All observers reported normal or corrected-to-normal vision and all except the one author were naive as to the purpose of the experiment. Procedures were approved by the local Institutional Review Board and all participants gave informed consent prior to participating.

Stimuli and procedure

Observers were tested individually in a quiet, dimly lit room. Head position was stabilized with a chinrest at a viewing distance of 46 cm (18.1 in). At this distance, 25.3 pixels subtended 1° of visual angle. Stimuli were presented on a 21 in (53.3 cm) ViewSonic color CRT monitor controlled by a Dell Dimension PC. The screen resolution was set to 1280×960 pixels and the refresh rate to 100 Hz. The program was written in MATLAB (The MathWorks) using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997).

Stimuli were white (83 cd/m²) on a dark background (0.3 cd/m²) and were drawn with a line width of 1 pixel (0.04°). The white fixation cross was $0.4° \times 0.4°$ (10×10 pixels) in length and positioned at the center of the display. The cues were open circles, each 1.74° (44 pixels) in diameter, equal to the length of each vernier line. The circles were displaced 5.54° (141 pixels) vertically from the origin, such that they were horizontally aligned with the lines. The horizontal cue–target distance varied across blocks of trials. The vernier lines were separated by a gap of 11.08° (284 pixels) from the bottom of the top line to the top of the bottom line. The mask consisted of a random grid of 128×96 black and white squares that covered the entire screen. Each square was 0.4° (10 pixels) in length and was black or white with equal probability. A new mask was generated on every trial.

The trial sequence is depicted in Figure 1. A warning beep, presented simultaneously with the onset of a fixation cross, alerted observers to the start of each trial. The fixation cross was presented for 1000 ms prior to the start of the trial sequence and observers were instructed to maintain fixation for the duration of the trial. Two cue circles were then presented for 30 ms in either the upper left and lower right or the upper right and lower left quadrants of the screen. Each cue configuration could appear with equal probability on any given trial. The cues were followed by an ISI of 150 ms. The vernier lines then were presented for 60 ms, followed by the mask (255 ms).

Observers responded to the line positions in a 2-alternative forced-choice (2AFC) task. They were instructed to press the left arrow key on the keyboard if they perceived the top line offset to the left of the bottom line and the right arrow key if they perceived the top line offset to the right of the bottom line. Trials were separated by 500 ms and a pause screen was presented once every 40 trials to

allow for breaks. No feedback regarding accuracy was provided.

Each block of trials consisted of two staircases run in parallel-one for each of the two cue configurations. The step size was 1 pixel (2.37′). On the first trial of every block, both vernier lines were aligned with the center of the display and with the fixation cross. If the observer's response indicated perceived offset away from the cue, the top line was subsequently shifted one step in the opposite direction (i.e., toward the top cue). Conversely, if the response indicated perceived offset toward the cue, then the top line was shifted away from the cue. On the next presentation, if the response was a reversal (i.e., different from the previous response), the same line was shifted back. Otherwise, the other line (the bottom line) was shifted one step toward or away from the cue based on the response. The program alternated the shifting of the top and bottom lines. This procedure ensured that the center of mass of the two vernier lines was never offset more than half step from the fixation cross. Reversals were counted jointly across both the top and bottom lines, and each block terminated once each staircase had gone through at least 15 reversals. The magnitude of the ARE was then measured by averaging across the line positions on the first 15 reversal points for each staircase (a total of 30 points) across all observers. This procedure provides a measure of the distance (in arc minutes) the vernier lines must be shifted toward the cues to cancel out the perceived repulsion. Positive values indicate perceived vernier offset opposite the two cue circles, and negative values indicate perceived vernier offset toward the cues (i.e., an attraction effect).

Observers completed at least 10 practice trials each, followed by eight blocks of trials, one for each cue–target distance. To control for possible learning effects, block order was randomized across participants. The cue–target distances, measured from the starting position of the vernier to the nearest edge of the cue outline, were 0.26°, 1.26°, 2.26°, 4.26°, 6.26°, 8.26°, 10.26°, and 12.26°. Observers completed an average of 833 trials ($SD = 225$) across all eight blocks.

Results

Estimates of the repulsion effect were obtained across the set of eight cue–target distances. As illustrated in Figure 2, the magnitude of the repulsion effect ranged from 3.15 to 7.11 arc min, with a mean of 5.53 arc min. One-sample t-tests were used to determine whether there was a significant repulsion effect above a hypothetical mean of zero (i.e., no repulsion effect). Eight two-tailed t-tests were carried out using a Sidak–Bonferroni correction for multiple comparisons ($\alpha_{S-B} = 0.0064$). The analysis revealed that the magnitude of the repulsion effect was significantly above zero ($p < 0.002$) at each distance.

To test the main hypothesis that the magnitude of the repulsion effect would vary as a function of cue–target distance, a one-way repeated measures ANOVA was run on the average thresholds using the Greenhouse–Geisser correction when appropriate. The analysis revealed a significant effect of cue–target distance, $F(2.69, 45.66) = 3.27$, $p = 0.03$, $\eta_p^2 = 0.16$. Finally, a trend analysis was used to characterize the relationship between cue–target distance and the size of the repulsion effect. Both the linear and quadratic trends were significant (linear: $F(1, 17) = 5.87$, $p = 0.03$, $\eta_p^2 = 0.26$; quadratic: $F(1, 17) = 4.45$, $p = 0.05$, $\eta_p^2 = 0.21$). All polynomial effects above the quadratic term were not significant, $p > 0.26$.
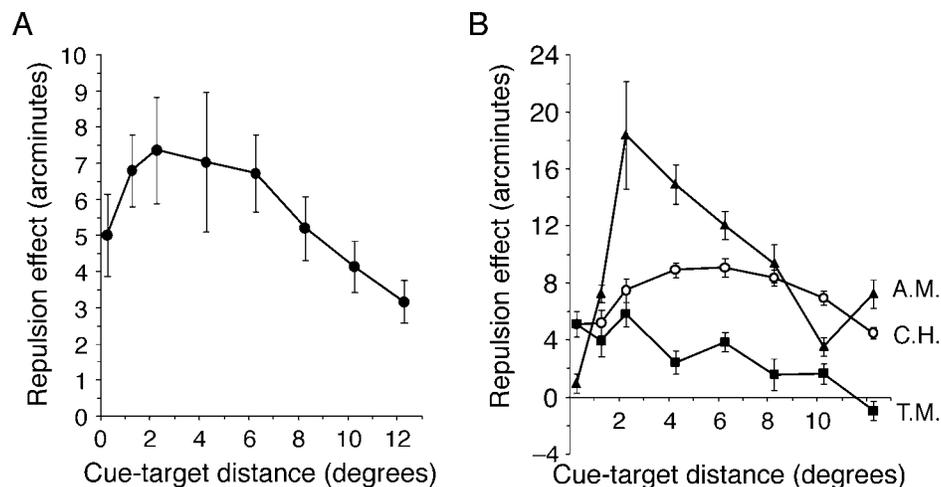

Figure 2. (A) Mean repulsion effect for all participants (left) as a function of the distance between the nearest part of the cue contour and the vernier target. (B) The same data for three of the participants. The error bars represent ±1 *SE*.

Discussion

The aim of the first experiment was to assess changes in the magnitude of the attentional repulsion effect (ARE) across a large range of cue–target distances. The repulsion effect was observed at each distance within the range tested, indicating that attention to the cues results in perceived vernier offset in the opposite direction regardless of distance. However, as Figure 2 illustrates, this relationship can be characterized by an inverted U-shaped function. The amount of perceived repulsion is attenuated at both close and far distances, with a maximum repulsion effect at a cue–target distance of approximately 2–4 degrees of visual angle.

It is important to note that Suzuki and Cavanagh (1997) previously concluded that the magnitude of the ARE is relatively independent of distance. However, the authors tested cue–target distances only between 2.1 and 7.7 degrees visual angle. The present data suggest that the distance dependence of the ARE is most pronounced at distances under 2° and above 8°.

Moreover, the present study found considerable individual variability in the distance that produced a maximal repulsion effect. To illustrate this, the right panel of Figure 2 shows the repulsion effect for three characteristic but different participants: A.M., C.H., and T.M. All three showed an attenuation of the repulsion effect at cue–target distances below 2° and above 8°, but the distance that produced a peak repulsion effect was different for each participant. Specifically, observers A.M. and T.M. showed a maximum repulsion effect at 2.26°, whereas C.H. showed a maximum effect at 6.26°. The cue–target distance that produces a maximum repulsion effect thus appears to be largely idiosyncratic. However, in order to control for order effects across participants, we randomized cue–target distances across blocks. Thus, for individual observers, differences in block order may explain in part the variation in the cue–target distance that produces the maximum repulsion. Nevertheless, the individual differences observed in this experiment suggest that a similar effect may have overridden any influences of cue–target distance on the size of the ARE in the original studies by Suzuki and Cavanagh.

Regardless of individual differences in the distance at which a maximum repulsion effect is observed, the present results suggest that when the cues and vernier target are placed sufficiently far apart, the magnitude of the ARE decreases. Therefore, we conclude that the size of the repulsion effect does depend on cue–target distance and this finding may be a consequence of the local nature of receptive field changes around the focus of attention reported in neurophysiological studies. The decrease in the size of the ARE with large cue–target distances may be also related to findings demonstrating that cuing effects on reaction time diminish as the distance between the cue and the target increases (e.g., Shulman, Sheehy, & Wilson, 1986). The results of this experiment thus point to another way in which reaction time effects reported in the cuing literature appear to closely follow the mislocalizations observed in the ARE (Pratt & Arnott, 2008). However, it is not known whether the observed effect of distance in this experiment relates to cue contour-to-target distance or cue center-to-target distance, as the two factors varied together in Experiment 1. The following experiments were designed to address this question.

Experiment 2

Although Experiment 1 established that cue–target distance can modulate the size of the ARE, we sought to further explore its underlying mechanisms. Specifically, does the ARE result from attention to the contour of the cue or from attention to the cue's center of mass? In other words, we sought to determine the locus of repulsion by examining whether the ARE is independent of variations in the form of the cues, and whether the mislocalizations observed in the ARE can occur around an "empty" region of space. This distinction between contour-based and center-of-mass-based repulsion has several implications. First, a number of studies have found target mislocalization effects toward or away from salient landmarks (e.g., Hubbard & Ruppel, 2000; Schmidt, Werner, & Diedrichsen, 2003), and these errors have been documented with retention intervals as short as 50 ms (Werner & Diedrichsen, 2002). Given the short target duration and the necessity of some delay (i.e., due to the presentation of a mask and the time required to manually respond to the vernier offset), it is possible that the ARE is a product of such contextual interactions between the cue contour and vernier target. Establishing a repulsion effect independent of variations in the cue contour would provide evidence that the ARE is distinct from the spatial distortions seen in these landmark effects.

Second, any model of spatial attention that assumes that attention can be directed away from the point of fixation also involves the assumption that the focus of attention is localized in some other region(s) of space. In the case of objects defined by luminance contours, such as the cues used in Experiment 1, it is not clear whether attention is drawn to the cue's center of mass or to a salient contour. A demonstration that attention is drawn to the centers of the cues rather than to their contours would provide further support for the proposal that it is spatial attention and not attention to object contours that acts to distort the perceived locations of the vernier lines.

Moreover, determining the locus of attention within the context of the attentional repulsion paradigm can offer insights into the broader question of which cue properties serve to guide automatic shifts of spatial attention and how the distribution of attention changes with variations in these properties. Previous research has shown that

altering cue size, for instance, can modify the size and spread of the attentional focus such that processing efficiency decreases when attention is distributed over a larger area (Castiello & Umilta, 1990). To the extent that cue manipulations shown to influence reaction times also influence the ARE (Pratt & Arnott, 2008), it is possible that similar manipulations may alter the size or even the direction of the ARE.

In Experiment 2, we modified the stimuli such that the cue contours were always one of the three sizes illustrated in Figure 3. For the two smaller sizes (Conditions 1 and 2), the cues were circles and the vernier lines lay outside the contour boundaries, as before. For the largest cue size (Condition 3), the cues were ovals elongated along the horizontal axis, and the locations of the vernier lines were all within the contour boundaries. The center of mass of the cues was kept constant across all conditions. If the ARE occurs relative to the closest contour, then in the condition with the largest cue size, one would expect the repulsion effect to occur in the opposite direction. In other words, there would be an "attraction effect" of the vernier lines toward the center of the cues. Alternatively, if attention is drawn to the cue centers, the perceived position of the vernier lines should be repelled away from the center of the cue regardless of the placement of the cue contours.

To allow for more precise, response-independent control of line position, this experiment employed the method of constant stimuli to quantify the repulsion effect. The
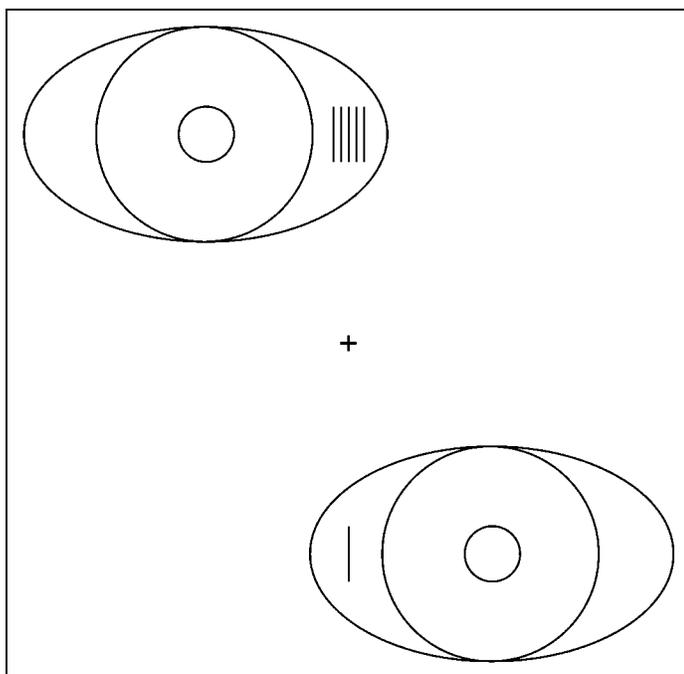

Figure 3. Stimuli used in Experiment 2, with each of the three cue conditions and set of five possible vernier positions superimposed above and below fixation. The three cue conditions were completed in separate blocks. Stimuli are drawn to scale.

percentage of "right" responses (i.e., responses that the top line appeared offset to the right of the bottom line) was obtained across a fixed set of five vernier positions. Thus, the experimental design was a 3 (Cue Shape) × 2 (Cue Configuration) × 5 (Target Position) factorial.

Methods

Participants

Twelve UC Berkeley undergraduates (8 females; mean age = 20.0, SD = 2.3) participated in exchange for course credit. All observers reported normal or corrected-to-normal vision and were naive to the purpose of the experiment. All gave informed consent prior to participating.

Stimuli and procedure

The apparatus and stimuli were identical to those described in Experiment 1, with the exception of the cue shapes and vernier positions as described below.

Two cues were presented either in the upper right and lower left or the upper left and lower right quadrants of the screen. Observers were instructed to maintain fixation throughout the trial. The cue configuration on each trial was randomly determined by the program with the constraint that each configuration appeared twice every four trials. Figure 3 depicts the three cue conditions in the upper left/lower right configuration with the five line positions superimposed. The cue shapes and sizes varied across blocks of trials. In every cue condition, the cues were centered on an imaginary point displaced 4.37° (111 pixels) horizontally from the central vernier line and were drawn with an outline of 4.74′ (2 pixels). In Condition 1, the circles were identical in diameter (1.74°) to those used in Experiment 1. In Condition 2, the cues were circles with a diameter of 6.66° (169 pixels). This condition was included to isolate the effects of increased cue size on the repulsion effect, while holding the origin of the cue circle constant. Finally, in Condition 3, the cues were ellipses elongated along the horizontal meridian, 10.96° (281 pixels) wide and 6.66° tall. The cues in the last two conditions were arranged such that the nearest outline of each cue at its horizontal midline was the same distance from the central vernier position. In Condition 2, the set of possible vernier positions was located outside the cue boundary, whereas the cue outline in Condition 3 bounded all possible vernier locations on the side opposite the cue's center of mass.

Following an interstimulus interval (ISI) of 150 ms, the vernier was presented for 60 ms. The bottom line was aligned with the fixation cross on every trial, while the top line was presented in one of five positions relative to the bottom line: −0.47°, −0.24°, 0°, +0.24°, or +0.47° (−12, −6, 0, +6, and +12 pixels, respectively). Negative values indicate that the top line was to the left of the bottom line

and positive values indicate that the top line was to the right of the bottom line. The top line position was determined randomly on each trial, with the constraint that each line position appeared once every five trials. As before, observers responded in a 2AFC task to vernier offset (i.e., left vs. right). Observers completed 10 practice trials, followed by three test blocks of 400 trials each. Block order was counterbalanced across participants such that there were two participants for each unique sequence of blocks out of a set of 6 possible combinations.

Results

[Figure 4](#) shows the percentage of "right" responses as a function of Vernier Position and Cue Configuration for the three Cue Shapes. The data were analyzed with a 3 (Cue Shape) $\times$ 2 (Cue Configuration) $\times$ 5 (Vernier Position) repeated measures ANOVA using the Greenhouse–Geisser correction when appropriate. The analysis showed no main effect of Cue Shape on the percentage of "right" responses, $F(2, 22) < 1$. As expected, there was a significant main effect of Cue Configuration ($F(1, 11) =$

19.14, $p = 0.001$, $\eta_p^2 = 0.64$), with the mean percentage of "right" responses being higher in the upper left and lower right configuration (61.7%) than in the upper right and lower left configuration (32.2%). This result replicates the standard repulsion effect found in previous studies using the method of constant stimuli (Pratt & Arnott, [2008](#)). There was a main effect of Vernier Position, $F(1.14, 12.50) = 57.26$, $p < 0.001$, $\eta_p^2 = 0.84$, with the percentage of "right" responses increasing as the top vernier was increasingly offset to the right. This result would be expected regardless of any repulsion effect and demonstrates that participants were sensitive to physical changes in the position of the lines.

In addition, the analysis revealed both significant Cue Shape $\times$ Vernier Position ($F(2.34, 25.73) = 3.48$, $p = 0.04$, $\eta_p^2 = 0.24$) and Cue Configuration $\times$ Vernier Position ($F(4, 44) = 20.61$, $p < 0.001$, $\eta_p^2 = 0.65$) interactions. The Cue Shape $\times$ Cue Configuration interaction ($F(1.29, 14.21) = 1.04$, $p = 0.19$) and the three-way interaction ($F(2.89, 31.76) = 1.08$, $p = 0.37$) were not significant.

The main effects of Position and Cue Configuration replicate the basic attentional repulsion effect, and the Cue Configuration $\times$ Vernier Position interaction appears to arise from a larger repulsion effect for smaller vernier
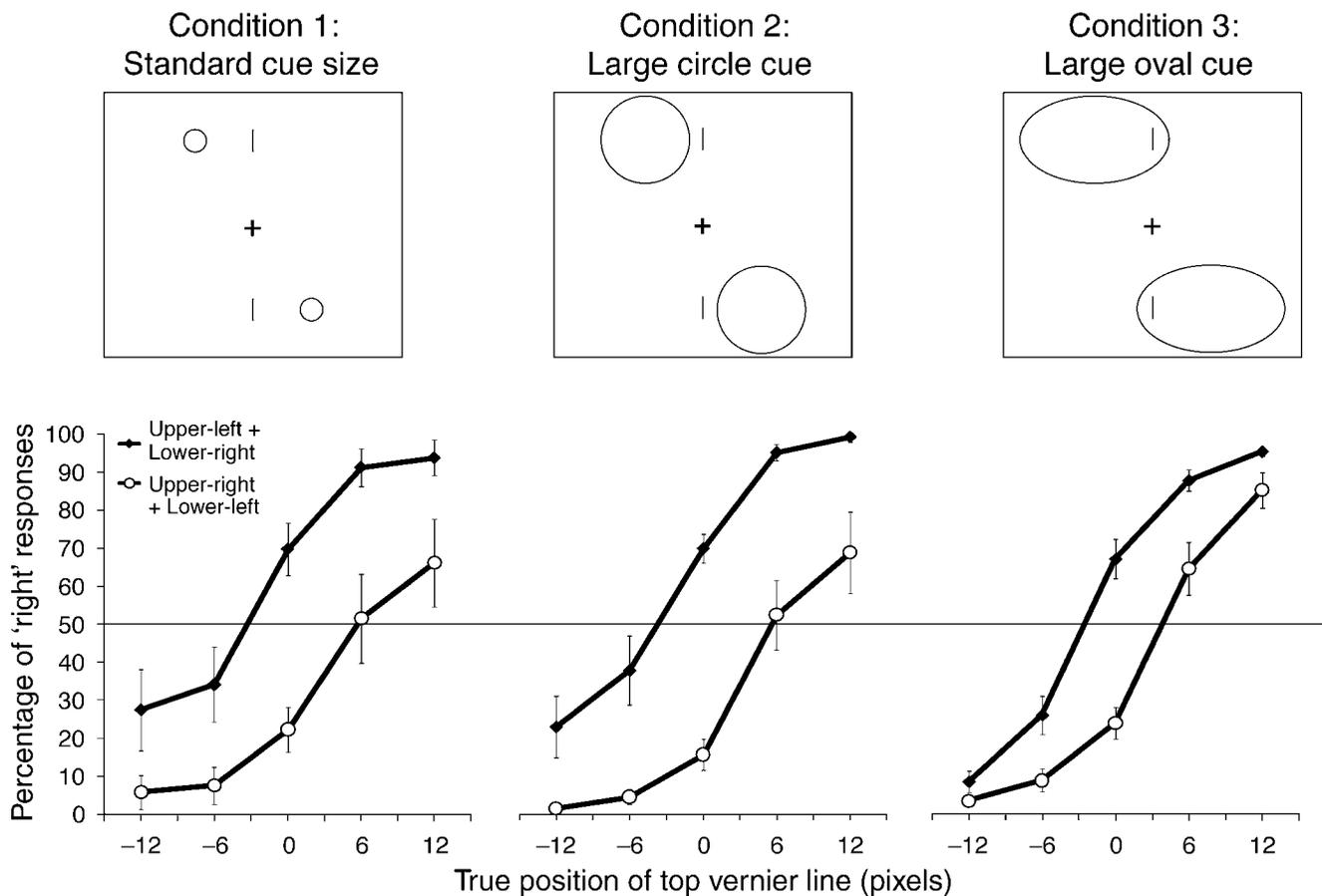

Figure 4. Percentage of "right" responses as a function of top vernier position for each of the two cue configurations and for each of the three cue shape conditions. The error bars represent ± 1 *SE*.

offsets than for larger ones. However, the Cue Shape × Vernier Position interaction suggests that manipulating the shape of the cue did change pattern of responses. Inspection of Figure 4 suggests that this interaction may result from a steeper slope in the function relating vernier offset to the percentage of "right" responses in Condition 3 relative to the two other conditions.

To examine the possibility that the ARE may also be reduced in Condition 3, difference scores in the percentage of "right" responses between the two cue configurations (upper left/lower right minus upper right/lower left) were calculated as an estimate of the size of the repulsion effect, leaving two factors in the analysis: Cue Shape and Vernier Position. We ran two post-hoc comparisons—the first between Condition 2 (large circle) and Condition 3 (large oval), and the second between Condition 1 (small circle) and Condition 2, using the Sidak–Bonferroni correction for multiple comparisons ($\alpha_{S-B} = 0.025$). Comparisons between Conditions 2 and 3 revealed a significant main effect of Cue Shape on the difference score, $F(1, 11) = 7.73$, $p = 0.02$, $\eta_p^2 = 0.41$. The mean difference score was smaller in Condition 3 (19.9%) than in Condition 2 (36.0%), suggesting that the repulsion effect was reduced when the cue contour bounded the vernier on the opposite side. Post-hoc comparisons were also run between Conditions 1 and 2 to examine the effects of cue size on the magnitude of the repulsion effect. The analysis showed no main effect of Cue Shape on the difference score $F(1, 11) < 1$. As expected, there was a main effect of Vernier Position, $F(4, 44) = 10.52$, $p < 0.001$, $\eta_p^2 = 0.49$. The Cue Shape × Vernier Position interaction was not significant, $F(4, 44) < 1$. Thus, increasing the cue size while keeping the center of mass constant did not appear to change the magnitude of the repulsion effect despite the fact that the closest cue contour was closer to the position of the vernier lines in Condition 2. However, changing the contours of the cue to encompass the vernier reduced the magnitude of the repulsion effect to some extent but did not eliminate it.

Discussion

Our findings in Experiment 2 are consistent with the claim that attention is attracted to the center of mass, an empty location within each cue. As in previous studies of the ARE, the cues in Condition 1 were equal in diameter to the length of one vernier line, and we replicated the basic repulsion effect in this condition. Moreover, the repulsion effect was present across the other two conditions. As shown in Figure 4, the percentage of "right" responses was always higher in the upper left and lower right cue configuration, regardless of the arrangement of the contours relative to the vernier lines. This finding suggests that the ARE is largely independent of the position of the cue contours. Instead, observers' attention

seems to be attracted to the center of the cue in each of the three conditions.

However, the fact that the repulsion effect did not reverse in Condition 3 (large oval) does not exclude the possibility that the position of the cue contour in relation to the vernier target might influence the pattern of responses as well as the magnitude of the repulsion effect. Differences in the percentage of "right" responses between the two cue configurations were smaller in Condition 3 relative to the two other conditions. The fact that the difference scores between the two cue configurations were reduced in Condition 3 relative to Condition 2 (large circle) suggests that the contextual relationship between the contour and vernier line can affect the magnitude of perceived repulsion, though it does not eliminate it. It is important to note that the distance between the vernier and nearest cue contour was equal between Conditions 2 and 3. Thus, any differences between these two conditions are attributable to contextual differences in the relative placement of the contours and not to the distance of the contours from the vernier lines. Together, these findings indicate that although the position of the cue contour might modulate the magnitude of the repulsion effect to some extent, the direction of the attentional repulsion effect is driven by a shift of attention to the cue's center of mass.

The results of the present study provide strong support for the hypothesis that the locus of attention is shifted to the center of mass of the cues, and that it is from this location that the repulsion effect arises. However, this claim is based on a lack of a significant change in ARE magnitude across different cue sizes and the fact that it is not eliminated when the cue contours bound the vernier lines on the opposite side. To provide a further test of the hypothesis that the ARE depends critically on the location of the cue's center of mass, we varied the distance between the vernier lines and the center of mass of the cues in Experiment 3.

Experiment 3

Experiment 3 was designed to test the hypothesis that when the distance from the vernier to the nearest contour of the cue is held constant, varying the center of mass of the cues changes the magnitude of the repulsion effect. To do so, we varied radius of the cues as depicted in Figure 5. The closest contours of each cue in every condition were arranged such that cue–target distance was identical. Importantly, this manipulation varied the cues' center of mass. In order to maintain the same contour-to-target distance, increasing the size of the cue requires its center of mass to be shifted more peripherally. The sizes of the cues were chosen to roughly approximate the range of sizes tested in the first two conditions of Experiment 2, as
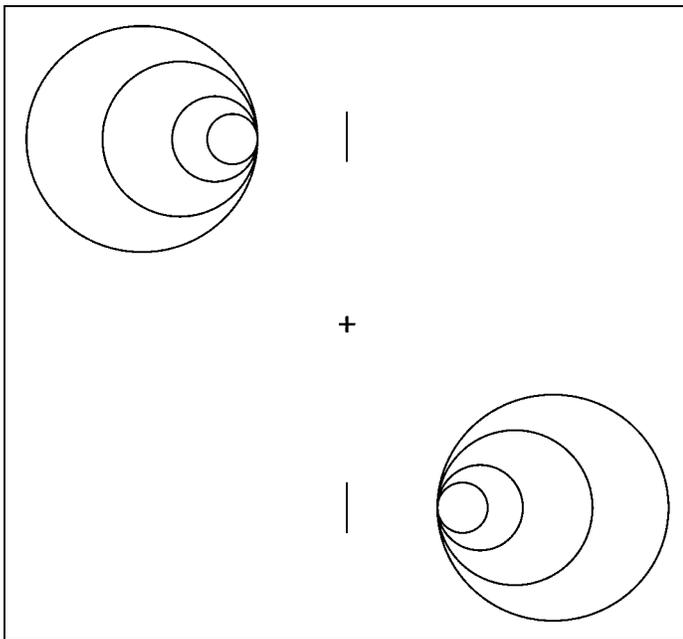
Figure 5. Stimuli used in Experiment 3, with each of the four cue sizes and vernier lines superimposed and drawn to scale.

no effect of cue size was found in the previous experiment. If the magnitude of the repulsion effect depends on the center of mass, one would expect the size of the ARE to follow a similar pattern to that seen in Experiment 1. In other words, as the distance between the vernier and the cue's center of mass increases, one would expect the magnitude of the ARE to show an inverted U shape. As in Experiment 1, the magnitude of the repulsion effect was measured using a staircase procedure to determine the amount of offset toward the cues required to eliminate the perceived repulsion.

Methods

Participants

Eleven UC Berkeley undergraduates (3 females, 8 males) participated in exchange for course credit. The mean age of the participants was 19.3 ($SD = 0.7$), with a range of 18 to 20. All observers reported normal or corrected-to-normal vision and were naive to the purpose of the experiment. All gave informed consent prior to participating.

Stimuli and procedure

The apparatus and stimuli were identical to those in Experiment 1, with the exception of cue size and position of its center.

The size of the circle cues varied across block of trials (randomized across participants). The cue diameters in each block were 1.74°, 3.0°, 5.5°, or 8° (44, 76, 140, and 202 pixels, respectively). The positions of the cues were

adjusted so that the cue–target distance from the vernier to the cue's nearest contour was always 3.13° (79 pixels). This required changing the distance between the central vernier position and the cue's center of mass in each cue condition to 4°, 4.63°, 5.88°, and 7.13°, respectively. Observers completed at least 10 practice trials, followed by four blocks of trials, one for each cue size. As in Experiment 1, each block terminated after at least 15 reversals. Observers completed an average of 348 trials ($SD = 40$) across the four blocks.

Results

Estimates of the repulsion effect were obtained for each cue radius by averaging across the vernier positions at each of the 15 reversal points for each of the two staircases (one for each cue configuration). As shown in Figure 6, the magnitude of the repulsion effect ranged from 2.98 to 5.25 arc min, with a mean repulsion effect of 4.38 arc min. As in Experiment 1, one-sample *t*-tests were carried out first to determine whether there was a significant repulsion effect above a comparison value of zero. Four two-tailed *t*-tests were carried out using the Sidak–Bonferroni adjustment for multiple comparisons ($\alpha_{S-B} = 0.0127$). The magnitude of the repulsion effect was significantly above zero in each condition, $p \leq 0.012$.

To test the hypothesis that the amount of perceived repulsion depends on the center of mass of the cues, a
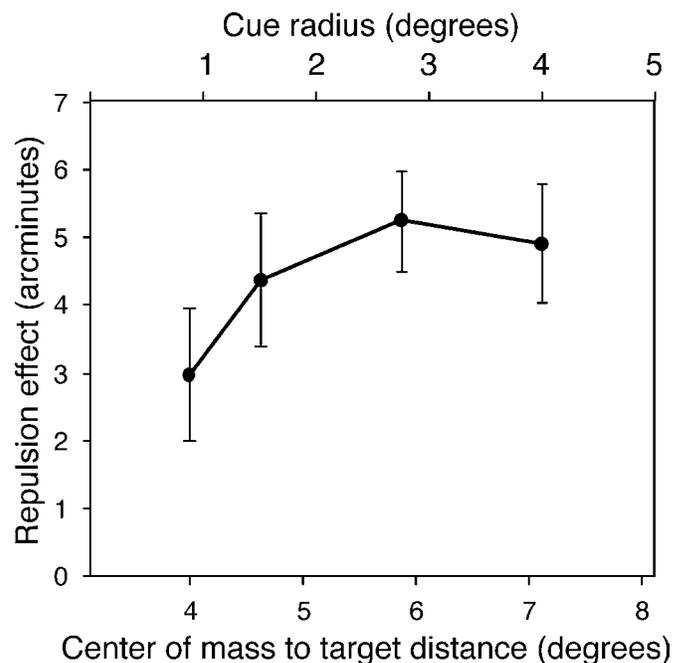

Figure 6. Mean repulsion effect for all participants as a function of cue radius and cue center-of-mass to target distance. The error bars represent ±1 *SE*.

one-way repeated measures ANOVA was run on the mean estimates of the repulsion effect. The analysis revealed a significant effect of Cue Center, $F(3,30) = 4.12$, $p = 0.02$, $\eta_p^2 = 0.29$. Finally, to examine the relationship between cue radius and the magnitude of the ARE, a trend analysis was run on the average estimates. This analysis revealed a significant linear trend ($F(1,10) = 8.09$, $p = 0.02$, $\eta_p^2 = 0.45$) and a significant quadratic trend ($F(1,10) = 4.90$, $p = 0.05$, $\eta_p^2 = 0.33$). The cubic term was not significant, $p = 0.78$.

Discussion

By measuring the ARE over a large range of cue sizes (0.87° to 4.0° in radius), we found that a concurrent increase in the size of the cues and the distance between their center of mass and the vernier does increase the magnitude of the repulsion effect. Importantly, Experiment 2 demonstrated that when the center of mass is held constant, manipulations of cue size do not change the size of the repulsion effect. Taken together, the results provide support that the critical factor was the center of mass of the cues in relation to the vernier lines. The findings in Experiments 2 and 3 therefore suggest that attention was attracted to the center of mass of each cue and it is the distance between the cues' center of mass and the location of the vernier targets that determines the magnitude of the ARE. Although cue contour manipulations may modify the magnitude of the repulsion effect, the present results suggest that the ARE is most sensitive to changes in the placement of the cues' center of mass.

Although the changes in the magnitude of the ARE did not show the expected inverted U shape across the cue sizes tested, we found a significant quadratic trend. In Experiment 1, the magnitude of the ARE peaked at a cue contour-to-target distance of 2.26° while large decreases in the magnitude of the ARE were present at distances above 8 degrees. At the distance with the largest ARE, the center of mass of the cues was located 3° from midline. In Experiment 3, the size of the ARE peaked at a cue radius of 2.75°, which corresponds to a distance of 5.88° between the cue's center of mass and the vernier lines when they are centered at midline. Thus, a shift in the relative peaks is seen across the two experiments. However, as noted above, in Experiment 1, the magnitude of the ARE did not begin to show large reductions until cue–target distance was increased to 8.26°, which corresponds to a distance of 9° between the center of mass of the cues and the vernier at midline. Had a larger range of distances between the center of mass and the vernier lines been tested here, it is possible that a larger drop in the magnitude of the ARE would have been found at the larger distances. However, as increases in distance were coupled with increases in the size of the cues, limitations exist on the maximum distances that can be tested.

Finally, although differences in the exact magnitude of the ARE are seen across these experiments, as shown in Figure 2 and as reported by Suzuki and Cavanagh (1997), there are significant individual differences in the size of the ARE across variations in distance and timing parameters. Thus, it is not the absolute values of the ARE that provide the critical test of the factors that drive the repulsion effect, but rather their relative changes across parameter values.

General discussion

Together, our experiments confirm the main findings reported by Suzuki and Cavanagh (1997), suggesting that attention to brief visual cues distorts the perceived locations of targets outside the focus of attention. However, attention seems to affect the perception of vernier offset in a spatially dependent manner. The first experiment showed that the amount of perceived repulsion is reduced at both small and large cue–target distances, with a maximum repulsion effect at a cue–target distance of approximately 2–4 degrees. The following experiments established that this pattern is driven primarily by shifts of attention to the cues' center of mass. Experiment 2 showed that although the ARE was reduced when the cue contour bounded the vernier target, the direction of the repulsion did not change. This suggests that the vernier lines are repelled from the centers of the cues rather than from their contours. Experiment 3 supported this conclusion by demonstrating that when cue contour-to-target distance is held constant, the magnitude of perceived repulsion changes as the center of mass is shifted more peripherally.

Critically, the relationship between the position of the cue's center of mass and the size of the ARE can be characterized by an inverted U-shaped function, as indicated by the significant quadratic trends in Experiments 1 and 3. The similarity in the pattern of results between Experiments 1 and 3 suggests that shifts of attention to the cue centers produced similar, distance-dependent mislocalizations of the vernier target, despite differences in the form of the cues between these two experiments. Moreover, this distinct profile of the ARE across a broad range of center-of-mass positions points to a common mechanism related to enhanced processing at the attended locations. A summary of the cue manipulations and findings from each of the three experiments is shown in Table 1.

Taken together, our results demonstrate that attention does not need to be anchored to an object to produce distortions in the perceived location of another target. Instead, these mislocalizations can occur independently of cue properties such as size and shape, provided that the cues induce shifts of attention to the same location—in this instance, an empty region of space. This finding

	Experiment 1	Experiment 2	Experiment 3
Cue center	Variable	Constant	Variable
Cue size	Constant	Variable	Variable
Distance to cue contour	Variable	Variable	Constant
Does size of ARE change?	Yes	No	Yes

Table 1. Summary of experiment results.

reinforces the role attention plays in producing the ARE, as it excludes explanations based on contextual interactions between the physical properties of the cue outline and the vernier target. The fact that the direction of the ARE did not change when the center of the cues' mass was held constant suggests that when presented with an outlined figure, such as a circular or oval cue used in these experiments, observers direct their attention to its center. In other words, the outlines serve to draw subjects' attention to the center of the figure rather than to its edges.

One implication of this finding is that observers seem to have rapid, automatic access to information about the position of an object's center. Previous research has shown that the visual system is able to rapidly and accurately extract summary information from sets of similar items (e.g., Ariely, 2001; Chong & Treisman, 2003). Importantly, this process can be applied to the extraction of position information outside of awareness. For instance, Alvarez and Oliva (2008) asked subjects to perform a difficult multiple-object tracking task and found that observers were much more accurate at localizing the centroid of the distracter objects than reporting on the position of any individual distracter. The authors argue that the visual system maintains moment-to-moment summary representations of unattended items—in this case, the centroid of a group of moving dots. This concept of center of mass seems to apply to representations of spatially extended objects as well. Another MOT study demonstrated that when required to track moving lines, observers automatically focus their attention on their centers, even when task demands favor a strategy of attending to their endpoints (Alvarez & Scholl, 2005).

Based on our findings, it appears that the visual system not only extracts such basic information from unattended items but also uses it to guide the deployment of spatial attention following the onset of a peripheral stimulus. Our results suggest that the center of the cue's mass serves as a target for exogenous shifts of spatial attention, even when it provides no information relevant to the task, and even when there is a salient object (in this case an outline) more proximal to the current focus of attention. One possible explanation for the existence of such a mechanism is that information about center of mass may be useful in obtaining a coarse representation of object position. This claim is further supported by research demonstrating that initial saccades tend to land near the center of gravity of objects (e.g., Coren & Hoenig, 1972; Vishwanath & Kowler, 2003).

As in other experiments employing exogenous cues to capture observers' attention, effects of attention on reaction time measures can been observed when the cue is not informative or predictive of target location (e.g., Posner, 1980). The findings from the present study and from the original experiments by Suzuki and Cavanagh (1997) have extended this principle to the domain of space perception. Our results complement those of Pratt and Arnott (2008) by demonstrating a number of similarities between cuing effects on reaction time and cuing effects on perceived location in the context of the ARE paradigm. For instance, just as cuing effects on reaction times decrease as the distance between the cue and the target increases (Shulman et al., 1986), the ARE also diminishes with large cue–target separations. It is conceivable that center-of-mass manipulations, such as those used in the present study, may have a similar effect on reaction times to targets within spatially extended cues.

Furthermore, the attentional repulsion effect has important implications for present models of visual spatial attention. Although many theories of attention assume that an observer's perception of space remains constant when attention shifts from one object to another, the attentional repulsion effect clearly demonstrates that this need not be the case. Attention that is attracted by sudden cue onsets as in the ARE paradigm can produce systematic distortions in an observer's perception of an object's location. Our findings are also broadly consistent with the three models proposed by Suzuki and Cavanagh (1997) to explain the attentional repulsion effect: RF recruitment, RF shrinking, and surround suppression. All three are related to the idea that the observed distortions in perceived location are produced by modulations in receptive field properties at or near the focus of attention. As the size of the ARE varies with cue manipulations that increase the distance between the center of mass and the target, it seems that these changes are greatest near the focus of attention—the center of mass of the cues. While the results from the present experiments support the models proposed by Suzuki and Cavanagh, they do not permit differentiation between them. A quantitative description of how changes in receptive field properties produce the ARE awaits a more comprehensive examination of the underlying neural mechanisms.

One remaining question is whether attentional repulsion might generalize to other types of stimuli. If the assumption that attention enhances space perception at attended areas at the expense of minimally attended ones is correct,

perceptual distortions should be documented in other paradigms as well. Indeed, several studies have offered some evidence for systematic errors under different attentional manipulations (e.g., Adam, Davelaar, van der Gouw, & Willems, 2008; Tsal & Bareket, 1999; Yamada, Kawabe, & Miura, 2008). These studies have used the observers' reproduction of target location with a cursor or pointing movement as a measure of perceived location. While this has proven to be a useful method for examining location perception in memory (e.g., Sheth & Shimojo, 2001), it may not be a sufficiently sensitive measure to record online stimulus perception. The attentional repulsion paradigm appears to have an advantage over the method of reproduction, as responses are categorical, eliminating any variance associated with motor and memory components in reproducing perceived target location.

Future research might employ methods similar to those used in the ARE paradigm, such as measurements of the point of subjective equality (PSE) in the distances between targets, to examine online stimulus perception. Recent studies using this approach have found changes in the perceived contrast of oriented Gabor patches following brief cues (Carrasco, Ling, & Read, 2004). Consistent with the notion that the ARE may be related to an expansion of visual space around the focus of attention, Anton-Erxleben, Henrich, and Treue (2007) reported that directing attention toward a cued location increased the perceived size of moving dot arrays. Future work in location perception may benefit from adopting similar approaches.

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