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The attentional repulsion effect and relative size judgments

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Abstract

Rapid shifts of involuntary attention have been shown to induce mislocalizations of nearby objects. One pattern of mislocalization, termed the Attentional Repulsion Effect (ARE), occurs when the onset of peripheral pre-cues lead to perceived shifts of subsequently presented stimuli away from the cued location. While the standard ARE configuration utilizes vernier lines, to date, all previous ARE studies have only assessed distortions along one direction and tested one spatial dimension (i.e., position or shape). The present study assessed the magnitude of the ARE using a novel stimulus configuration. Across three experiments participants judged which of two rectangles on the left or right side of the display appeared wider or taller. Pre-cues were used in Experiments 1 and 2. Results show equivalent perceived expansions in the width and height of the pre-cued rectangle in addition to baseline asymmetries in left/right relative size under no-cue conditions. Altering cue locations led to shifts in the perceived location of the same rectangles, demonstrating distortions in perceived shape and location using the same stimuli and cues. Experiment 3 demonstrates that rectangles are perceived as larger in the periphery compared to fixation, suggesting that eye movements cannot account for results from Experiments 1 and 2. The results support the hypothesis that the ARE reflects a localized, symmetrical warping of visual space that impacts multiple aspects of spatial and object perception.

Keywords Attentional repulsion effect · Visual space · Size perception · Exogenous attention · Involuntary attention · Pseudoneglect

Introduction

The ability for visual attention to be involuntarily drawn to specific regions of space provides an important mechanism through which individuals are able to rapidly orient towards and respond to external events in their environment. This reflexive orienting has been labeled involuntary or exogenous attention, highlighting the fact that changes in attentional state are stimulus-driven (Jonides, 1981; Posner, 1980). This contrasts with voluntary or endogenous attention, where changes are based on the intentions or goals of an individual (Carrasco, 2011; Jonides, 1981; Nakayama & Mackeben, 1989). Traditionally, involuntary attention studies have focused on changes in reaction times or discrimination/detection ability to measure changes across attentional states. However, other lines of research have examined how involuntary attention can alter perceptual qualities, such as perceived contrast (Carrasco, Penpeci-Talgar, & Eckstein, 2000), object size (Anton-Erxleben, Henrich, & Treue, 2007), and spatial resolution (Anton-Erxleben & Carrasco, 2013; Yeshurun & Carrasco, 1998).

Complementing this work is a series of studies that have investigated the impact of attentional shifts on the underlying structure of visual space. In particular, research has shown that rapid shifts of attentional focus toward involuntary cues lead to systematic distortions in the perceived location of subsequently presented lines away from the cued location, termed the Attentional Repulsion Effect (ARE) by the authors of the original study (Suzuki & Cavanagh, 1997). Across seven experiments, Suzuki and Cavanagh (1997) showed that two vertically oriented vernier lines aligned above and below a fixation point appeared to be shifted away from two circular pre-

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cues that were briefly flashed along a diagonal (Fig. 1a, left panel). This effect could not be explained by quick adaptation to the circular cues or apparent motion, could also be induced with voluntary cues, and the effect with involuntary cues was found to have a similar curve to reaction time effects (Nakayama & Mackeben, 1989). That is, the ARE peaked with a stimulus onset asynchrony of around 200 ms and declined in magnitude as the stimulus onset asynchrony increased, supporting an attentional basis for the effect. These results are consistent with Pratt and Arnott (2008), who showed that the same factors known to modulate reaction time in involuntary attention paradigms also modulate perceived location in ARE paradigms, including single onset, offset, onset-off, and color pop-out displays, further supporting an attentional basis for the ARE effect. However, we note that other experiments have found dissociations between cue-induced reaction time and ARE effects (Gozli & Pratt, 2012). Thus, questions still remain regarding the extent to which cue-induced changes in object location correspond with measured changes in reaction time effects.

In a different line of investigation, studies have examined how varying cue-target spatial relationships and stimulus shapes impact the magnitude of the ARE (see Fig. 1a). One study (Kosovicheva, Fortenbaugh, & Robertson, 2010)

showed that the point around which the ARE warps perceived space is the center of the cue stimulus, even when no stimulus contour exists there (Fig. 1a, left panel). By manipulating the size and shape of the inducing cue, Kosovicheva et al. (2010) showed that even when the cue contours were made so large that the actual contour of the cue circle crossed the vertical meridian onto the other side of the vernier lines, the direction of the ARE was the same as with smaller cue circles. This was consistent with a repulsion in perceived location away from the center of mass of the cues. Another study (Fortenbaugh, Prinzmetal, & Robertson, 2011) provided support for the notion that the impact of the cues briefly alters the underlying structure of visual space, and not just perceived relative location (Fig. 1a, right panel). Specifically, this study showed that the perceived shape of a single target oval could be systematically distorted, making the oval look wider or taller, depending on the relative position of the cues to the oval contour along the horizontal or vertical meridian. Finally, another recent study (Toba, Cavanagh, & Bartolomeo, 2011) used a variant of a bisection task, called the Landmark Task (Harvey, Milner, & Roberts, 1995), to determine if small single dot cues would impact the perceived midpoint of a line segment (Fig. 1a, middle panel). Results of this study showed that the cue systematically biased midpoint judgments away
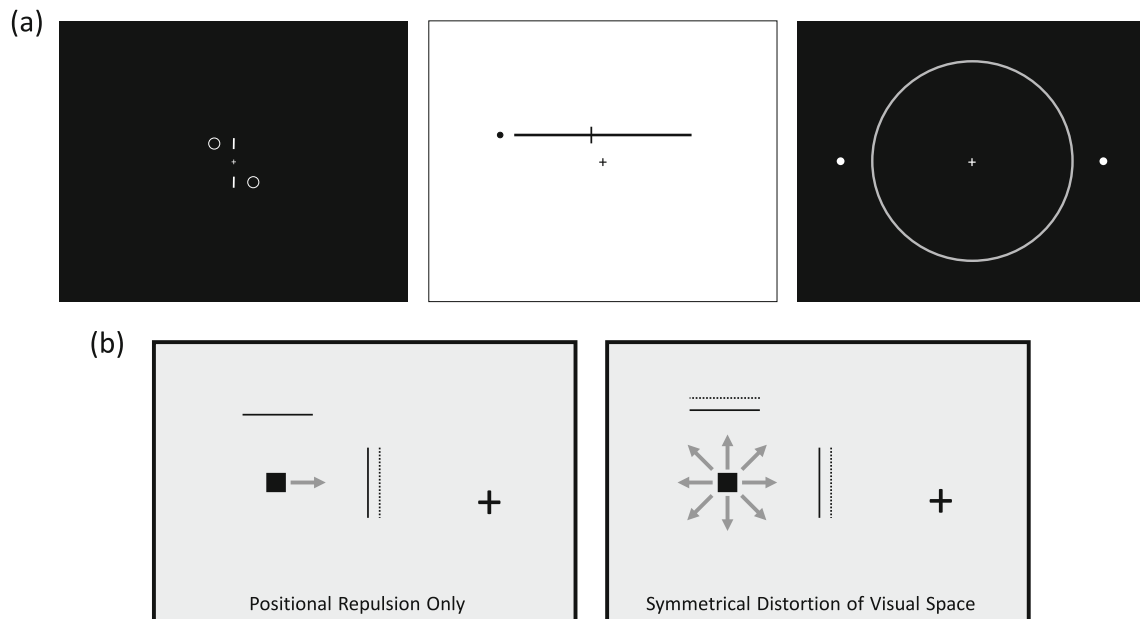

Fig. 1 Schematics showing previous stimulus configurations used to study the Attentional Repulsion Effect (ARE) and potential sources of distortion. (a) The left panel show the standard design developed by Suzuki and Cavanagh (1997) and used by most studies of the ARE, including Kosovicheva et al. (2010). The middle panel shows the design used by Toba et al. (2011) to study the impact of the black dot cues on the perceived midpoint of the line using the Landmark Task. The right panel shows the design used by Fortenbaugh et al. (2011) to study the impact of the white cue dots on the perceived shape of a single blue oval. These illustrations show the relative placements of the cues and targets and are not drawn to scale. (b) The panels show two potential patterns of distortions that could underlie the ARE effect. The repulsion only hypothesis (left panel) suggests that distortions in location only occur in the direction parallel to attentional shifts from fixation to the peripheral cue. In contrast, the symmetrical distortion of visual space hypothesis predicts a shift in perceived location radiating symmetrically out from the location of the cue. Here the cue is shown as the black square, the target object is shown as a solid black line and the perceived location of that target object is shown as a dotted line. The grey arrows indicate the direction of the distortion(s) in visual space.

from the direction of the cue, consistent with a perceived elongation of the horizontal line segment or a shift in the vertical transector line away from the cued side.

Collectively, these studies have shown that the ARE is exhibited under a variety of cueing and stimulus configurations. However, all of the stimulus configuration designs used to date are only able to assess changes in perceived location or object size along a single radial direction (see Fig. 1b). That is, all have shown shifts in position or object contours in the opposite direction of the attentional shift from the fixation point out to the location of the peripheral cue (see Fig. 1b, left panel). However, in proposing a potential neural mechanism underlying the ARE, Suzuki and Cavanagh (1997) note three potential alterations in receptive field properties that could explain the distortion in perceived location, and have been observed in neurophysiological studies of attention. Of particular relevance is a single-cell recording study by Connor et al. (1996) that was used by Suzuki and Cavanagh (1997) to support a receptive field shifting mechanism. This study measured not only the changes in single-cell V4 neuron receptive field profiles with attentional shifts away from the point of fixation, but also the spatial distribution of these receptive field changes. Specifically, this study found evidence for shifts in the receptive fields of neurons toward the cued locations. Importantly, the authors also found evidence for shifts in receptive field profiles surrounding the cued location, and not just along the radial direction connecting a given neuron's classical receptive field center to fixation. This finding in particular suggests that if the ARE is driven by transient shifts in receptive field properties around the locus of an involuntary cue, then the resulting distortion in the underlying representation of visual space should lead not only to the classic "repulsion" effect, but also symmetrical distortions in perceived location and shape around the cued location (Fig. 1b, right panel). Additionally, this distortion should not just be seen in perceived relative location judgments as measured with the standard ARE configuration using vernier lines. Rather, the type of observed distortion will depend on the cue-target spatial configuration and the type of response that participants are asked to provide (e.g., position, size, shape), because the basis for the distortion is a localized warping in the underlying metric of visual space, which will impact all aspects of spatial processing for objects presented in that distorted space.

The present study tested the hypothesis that perceptual distortions exist around the location of the cue and not just along a single direction using a novel stimulus design (see Fig. 2). Adopting a paradigm that has been used to assess intrinsic left-right asymmetries in perceived width by adding pre-cues that attract involuntary attention (Charles, Sahraie, & McGeorge, 2007; Milner & Harvey, 1995; Milner, Harvey, & Pritchard, 1998), this paradigm allowed us to assess changes in the perceived width and perceived height of the stimuli.
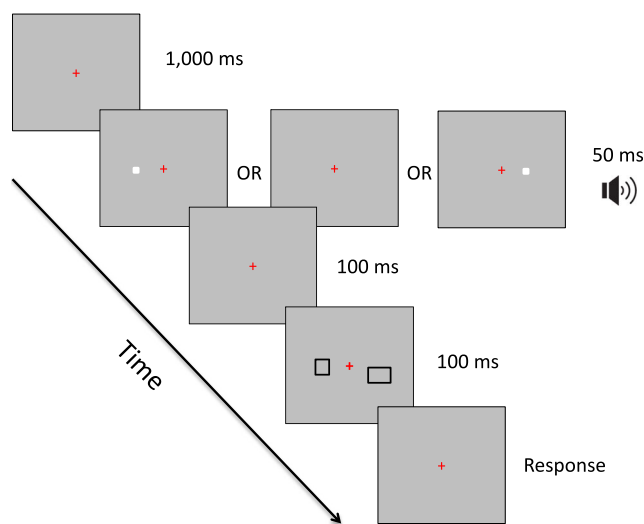
Fig. 2 Experimental design. Schematic illustrating the time course of stimulus presentation during each trial and the three potential cue locations. Stimuli are not drawn to scale

Systematic increases in the perceived width of cued objects would be consistent with previously observed results from ARE studies (see Fig. 1b, left panel). However, corresponding increases in perceived height, the orthogonal direction to the fixation-cue directional shift, would provide support for the ARE being driven by shifts in receptive fields toward the cued location as seen in single-cell recording studies (see Fig. 1b, right panel). Additionally, by altering the experimental dimension from size to position across Experiments 1 and 2, we tested whether distortions would be observed across multiple stimulus spatial properties using the same cue and target objects, consistent with a generalized distortion impacting the underlying metric of visual space.

Experiment 1

The goal of the first experiment was to test the hypothesis that similar distortions in perceived shape should be seen across multiple stimulus dimensions (i.e., perceived width and height) using the same lateral cue design. For this experiment, rectangles presented on the left and right side of the display were pre-cued and participants were asked to make judgments about the relative width or height of the rectangles using the method of constant stimuli. Of note, an ARE effect operating on these rectangles is expected to make the cued rectangle appear larger along the tested dimension. If the cued rectangle is perceptually expanded, then in order for the cued and non-cued rectangles to appear equivalent, the cued rectangle would need to be physically smaller along the tested dimension to account for the perceptual expansion. Thus, we predicted that perceptual expansions along the width and height dimensions for the cued rectangles would be measured by shifts in the

point of subjective equality toward smaller physical sizes with the magnitude of the shift being equivalent in the width and height dimensions.

Methods

Participants

This experiment used a mixed design with 32 naïve undergraduate participants completing the experiment for course credit. Out of these 32 participants, 16 participants (11 females; mean age=21.9 ± 5.7 years) were assigned to the width judgment condition and the other 16 participants (14 females; mean age = 22.3 ± 2.1 years) were assigned to the height judgment condition. All participants self-reported being right-handed and having normal (20/20) or corrected-to-normal vision. Participants with ocular disorders were excluded from participating. One participant did not follow instructions for the height judgment task and we were unable to effectively model this participant's data ($R^2 < 0.05$ for two conditions). Data from this participant were excluded in the following analyses. This research was approved by the University of California's Committee for the Protection of Human Subjects and followed the tenets of the Declaration of Helsinki.

Power analysis and sample size calculation Previous studies calculating the magnitude of the ARE have used varied sample sizes ranging from three to 18 participants. To determine the appropriate sample size for this study we calculated power analyses using the software program G*Power v3.1 (Faul, Erdfelder, Lang, & Buchner, 2007). First, we estimated the sample size needed to detect the ARE using one-sample t-tests comparing the measured distortion to a hypothetical mean of zero. For this we used data from the condition closest to the stimulus design used in the present study, namely the 1.26° cue-center to contour distance in Experiment 1 of Kosovicheva et al. (2010). Using the mean PSE and standard deviation across the 18 participants in this experiment, results of the power analysis estimate a total sample size of eight participants are needed to achieve 95% power to detect the ARE. While the ARE is large and requires small sample sizes, our present study includes comparisons across multiple cue locations. To approximate the sample size needed for these repeated measures ANOVAs, we used the data from Experiment 1 of Fortenbaugh et al. (2011) for which the data and effect sizes were available for the interaction term of interest. Power analyses calculated estimate a sample size of 14 participants needed to have 95% power. Terminating recruitment after achieving a sample size of 16 participants per task was thus deemed to provide the power needed to detect any potential significant effects across all analyses of interest in this experiment.

Materials and procedure The experiment was conducted on a ViewSonic G225f CRT monitor (refresh rate = 100 Hz). Stimuli were generated by Presentation software (Version 11.1, www.neurobs.com) and presented against a gray background (25 cd/m^2). Viewing distance was set at 60 cm. Prior to beginning the experiment, the height of the monitor was adjusted for each of the participants to allow them to comfortably fixate a red cross located at the center of the monitor without tilting his/her head up or down. A chin and forehead rest stabilized head position throughout the experiment.

Figure 2 shows an example of a trial sequence. On every trial the participants first viewed a red fixation cross (0.5° × 0.5°) alone for 1,000 ms. Participants were told to maintain fixation on the center cross throughout each trial. A brief tone then sounded for 50 ms. During this time, the fixation cross was presented along with a small white square, the involuntary "cue," on the left or right side of the display (1.0° × 1.0° centered at 6.5° eccentricity along the horizontal meridian), or the fixation cross was presented alone in non-cued trials. After a 100-ms inter-stimulus interval (ISI) when the fixation cross was again shown alone, the two black rectangles (0.25° outline thickness) were presented for 100 ms with the fixation cross. A blank screen was then presented until participants responded. Reaction times were not recorded as the focus of this experiment was on accuracy and participants were given as much time as needed to respond before the next trial appeared.

Participants were assigned one of the tasks and completed two blocks of trials in each task. Participants who completed the width judgment task chose which of the two rectangles they perceived as being wider in one block by pressing the left or right arrow key, corresponding to the rectangle on the left or right side of the display, respectively. In the other block of trials, they determined which rectangle they perceived as being thinner. Again, this was done by pressing the left or right arrow key in order to select the rectangle on the left or right side of the display, respectively. Participants who completed the height judgment task determined which rectangle appeared taller in one block while in the other block they chose which rectangle appeared shorter, again using the corresponding left/right arrow keys to respond. Participants were asked to make both types of responses (wider/thinner or taller/shorter) to control for response biases that might be induced in cases of uncertainty (e.g., when the two rectangles were in fact equivalent) that could be influenced by the side of the cue. To control for order effects in the sample, block order was alternated across subjects so that every other participant completed the experiment beginning with the wider/taller trials and ending with thinner/shorter trials. The other half of the participants completed the experiment beginning with thinner/shorter trials and ending with wider/taller trials.

On half of the trials the standard (3.0° × 3.0°) rectangle was presented on the left/right side of the display. The control

dimension of the comparison rectangle (height for participants who were judging perceived width, width for participants who were judging perceived height) was always 3.0° while seven different variants of the dimension of interest (width or height) were tested (2.6°, 2.8°, 2.9°, 3.0°, 3.1°, 3.2°, and 3.4°). The foveal edges of the two rectangles were fixed at 5.0°, maintaining a 10° separation between the two rectangles. That is, the 3.4° comparison rectangles extended further into the visual periphery than the 2.6° comparison rectangles. Fixing the location of the foveal edge prevented participants from using the distance between the inner rectangle edges and the fixation cross in their size judgments. The standard rectangle was vertically centered on the horizontal meridian. On half of the trials the comparison rectangle was centered 0.5° above the horizontal meridian and on the other half it was centered 0.5° below the horizontal meridian. This was done to ensure that the top and bottom edges of the two rectangles were not collinear and could not be used to compare the vertical dimension (i.e., height) of the two rectangles. Across the three cue conditions (left/none/right), two comparison rectangle sides (left/right), two relative heights (±0.5° vertical offset) of the comparison rectangle, and seven possible comparison variants, each condition was repeated four times within a block for a total of 336 trials within each block. Thus, each participant completed a total of 672 trials across the two response types. Two breaks were given during each block.

Before beginning each block of trials, participants were given ten practice trials to familiarize them with the task and the response necessary (wider/thinner or taller/shorter). The trial sequence was the same as the experimental trials with the following two exceptions. First, the potential variable dimension (width or height) of the comparison rectangles were decreased/increased with no dimension of interest equivalent to the standard rectangle (2.4°, 2.6°, 2.8°, 3.2°, 3.4°, and 3.6°) to make the task easier during practice. Second, practice trials also included feedback. If participants responded incorrectly, a tone was sounded for 50 ms and the words "Incorrect Response" appeared on the screen for 1,000 ms before the next trial began.

Results

To control for any potential response biases that could occur in the case of uncertainty and potentially be driven by the cue location, two response types were collected for each task (wider/thinner and taller/shorter). We note that additional analyses not presented in the text were completed that included response type as a factor. No significant main effects or interactions with the response types were observed. As no significant patterns were observed across the response type factor, in the following analyses responses were flipped for the block where participants responded which rectangle appeared thinner/shorter so that trials across the two blocks could be

combined (e.g., all responses correspond to which rectangle appeared larger across the dimension of interest). Data were also collapsed across the two relative vertical offset conditions for the comparison rectangle, as again this control was used to prevent participants from using collinearity when making height judgments.

Shifts in point of subjective equality across cue positions
Across the six combinations of 2 Comparison Sides (left/right) and 3 Cue Conditions (left/none/right), the proportion of trials that participants responded that the comparison rectangle was larger than the standard rectangle was calculated for each of the seven comparison sizes tested. Thus, the proportion of trials that participants responded that the comparison rectangle was larger (i.e., wider or taller depending on group assignment) than the standard along the dimension of interest was calculated from the 16 trials in each of these 42 conditions (i.e., collapsing over relative vertical offset and response type conditions). Cumulative Gaussian functions were then fit to the data (GraphPad Prism; GraphPad Software, Inc) to determine the point of subjective equality (PSE), or how wide/tall the comparison rectangle needed to be in each condition to be perceived as equivalent to the width/height of the standard rectangle. For illustrative purposes, Fig. 3 shows the group-level means of the proportion of times the comparison rectangle was perceived as larger along the dimension of interest than the standard as a function of the comparison width (Fig. 3a) or height (Fig. 3b), the side of the comparison rectangle, and the side of the display the cue was presented, fitted with cumulative Gaussian functions. As can be seen in Fig. 3, the side of the cue impacted the perceived width/height of the comparison rectangles across the range of comparison sizes tested. However, here we focus analyses on the shift in the PSE for the comparison rectangle.

Figure 4a and c show the mean PSE for the left and right comparison conditions in the three cue conditions when participants were asked to make width or height judgments, respectively. A 2 Comparison Side × 3 Cue Condition × 2 Task Type (width/height judgments) mixed-design ANOVA with Task Type as a between-subjects factor was calculated on the individual subject PSEs using SPSS v24 with effect sizes calculated using partial η^2 values. Results show no main effect of Comparison Side, $F(1,29) = 0.011$, $p = 0.92$, $\eta^2 < 0.01$, and no overall difference across Task Type, $F(1,29) = 1.254$, $p = 0.27$, $\eta^2 = 0.041$. There was a significant main effect of Cue Side, $F(2,58) = 3.609$, $p = 0.033$, $\eta^2 = 0.111$ with PSEs being overall smaller in the no-cue condition relative to the left or right cue side conditions. Task Type did not interact with Cue Side, $F(2,58) = 1.203$, $p = 0.308$, $\eta^2 = 0.040$. However, there was a Task Type × Comparison Side interaction, $F(1,29) = 8.628$, $p = 0.006$, $\eta^2 = 0.229$, with smaller PSEs for the left comparison relative to the right comparison rectangle when participants were judging perceived width. However, the
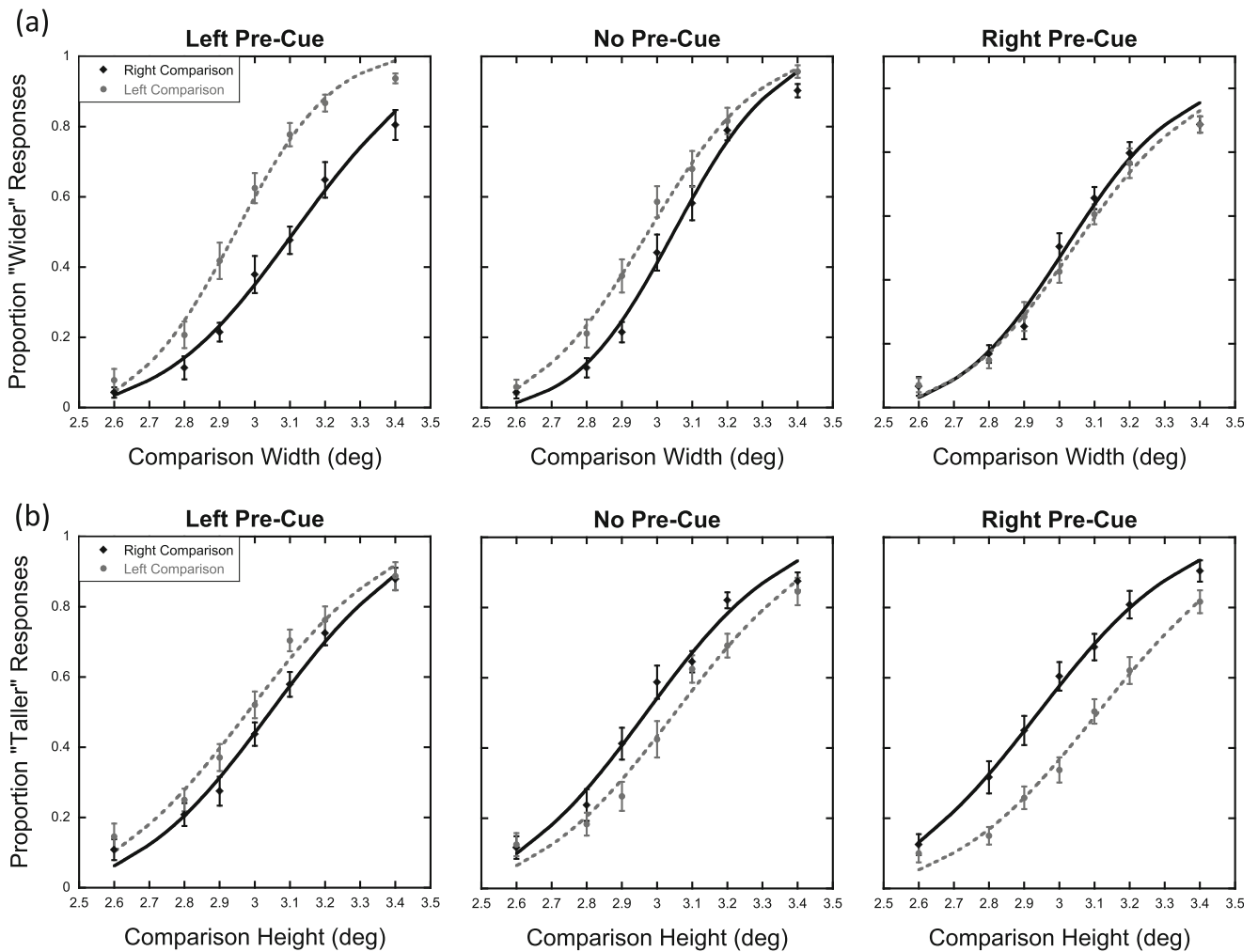
Fig. 3 Experiment 1 group means. Plots showing the mean proportion of time participants responded that the comparison rectangle was (**a**) wider or (**b**) taller than the standard rectangle for the seven comparison variants tested as a function of which side the comparison was on (left/right) and the side that the pre-cue was tested on. Curves show the best fitting cumulative Gaussian function for the group means. Error bars show ±1 SEM

opposite pattern in PSEs was seen when participants were judging perceived height. The main interaction of interest for this experiment, the Cue Side × Comparison Side interaction, was also significant, $F(2,58)=19.205$, $p < 0.001$, $\eta^2 = 0.398$. As seen in Figs. 4a and c, PSEs increased monotonically as the cue moved from the left side, to the no-cue, to the right-side conditions when the comparison rectangle was on the left side of the display, while the opposite pattern was observed for right comparison rectangle. This is consistent with the rectangle on the cued side of the display being perceptually expanded along the measured dimension, as again, smaller PSEs in the physical size of the comparison rectangle would be needed to correct for a perceptual expansion in order for the two rectangles to appear equivalent. Importantly, no three-way interaction was observed, $F(2,58) = 0.086$, $p = 0.92$, $\eta^2 = 0.003$, suggesting that the Cue Side × Comparison interaction was of similar magnitude regardless of the type of response judgments made.

Quantifying the magnitude of the ARE distortion To further examine the magnitude of the cueing effect on the size asymmetry, for each of the three cue conditions in each of the two response judgment groups, difference scores were calculated for each participant by subtracting the PSE when the comparison rectangle was presented on the left side of the display from the PSE when the comparison rectangle was presented on the right side of the display. Figures 4b and 4d show the six difference scores for the three cue conditions for the width and height judgments groups, respectively. As seen in Figs. 4b and 4d, despite the inherent asymmetry in size perception across the left and right rectangles that is seen in the no-cue condition, the degree to which the cue served to alter the perceived size of the rectangles was similar for both the left and right cues. The magnitude of this shift with cue position relative to the no-cue condition represents the magnitude of the Attentional Repulsion Effect (ARE), and can be quantified by subtracting the difference score in the no-cue condition (e.g., each

(a)

(b)

(c)

(d)
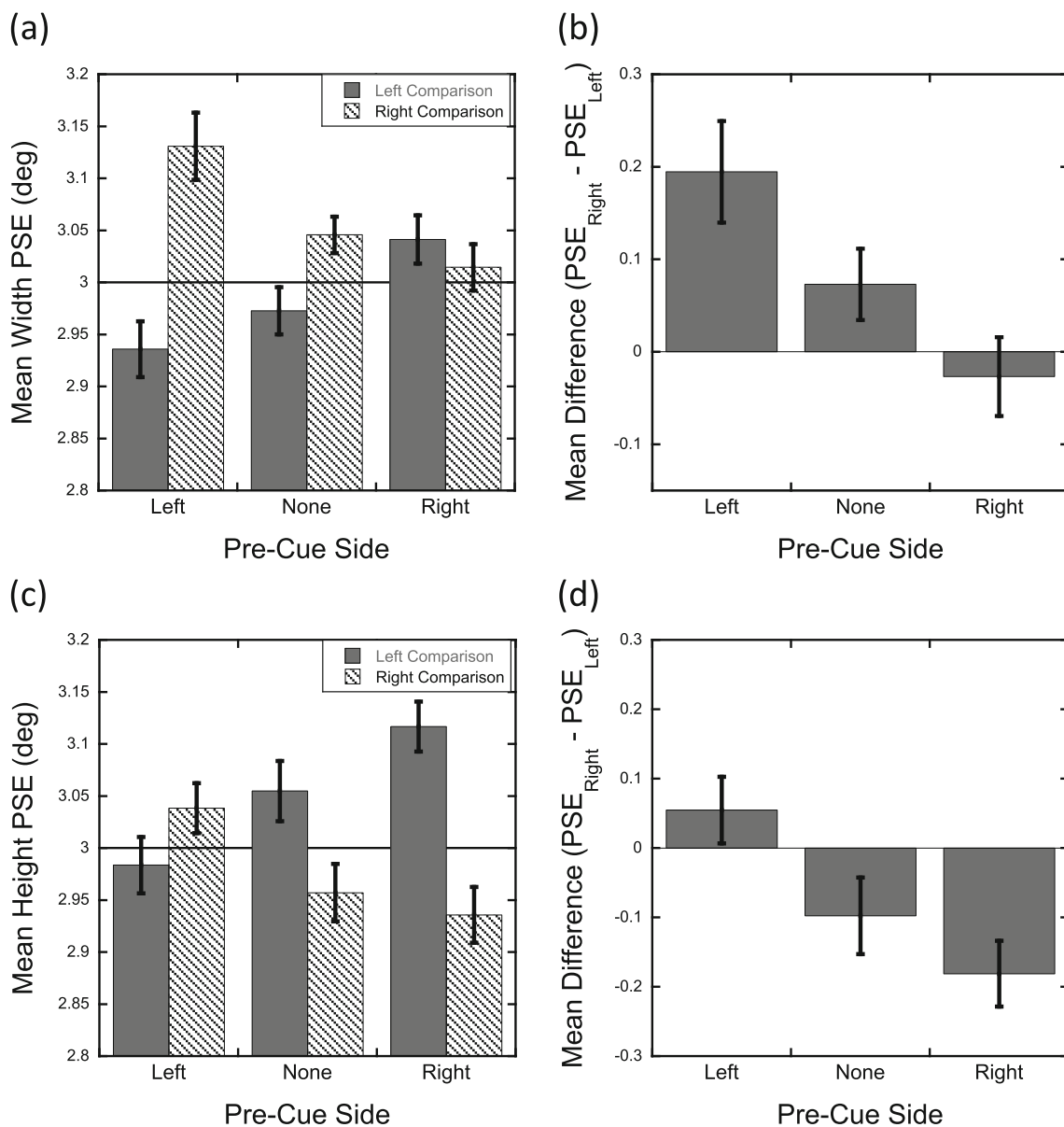
Fig. 4 Experiment 1 point of subjective equality. (**a, c**) Bar graphs showing the mean horizontal (**a**) and vertical (**c**) PSE for the comparison rectangle as a function of pre-cue side and the relative side of the comparison rectangle. The solid horizontal lines show the expected PSE if no distortion were present given that the standard rectangle always had a width/height of 3.0°. (**b, d**) Bar graphs showing the change in PSE for the comparison rectangle when it was presented on the right side compared to the left side for each of the three cue conditions. The magnitude of the ARE is the shift from the No Pre-Cue condition to the other two bars. All error bars show ±1 SEM

participant's baseline asymmetry) from the difference scores in the left and right cue side conditions. The sign of the ARE was then flipped for the right cue condition so that larger expected ARE magnitudes were reflected by larger positive values.

For the width judgment task, comparison of the left and right ARE magnitudes showed that cueing the left side of the display increased the perceived width of rectangles on the left side of the display by 0.12° ± 0.05° (95% CI: 0.021–0.2224) on average while cueing the right side of the display increased the perceived width of rectangles on the right side of the display by 0.10° ± 0.04° (95% CI: 0.015–0.184). Paired-sample t-tests were calculated to compare the magnitude of

the ARE for the left and right cue sides, with effect size measured using Cohen's d. Results showed no difference in the magnitude of the ARE, $t(15) = 0.34$, $p = 0.74$, $d = 0.09$. Additionally, one-sample tests showed that the magnitude of the ARE was significantly greater than zero for both the left cue, $t(15) = 2.57$, $p = 0.02$, $d = 0.64$, and the right cue conditions, $t(15) = 2.51$, $p = 0.02$, $d = 0.63$.

For the height judgment task, difference calculations showed that cueing the left side of the display increased the perceived height of rectangles on the left side of the display by 0.15° ± 0.02° (95% CI: 0.116–0.190) on average while cueing the right side of the display increased the perceived height of

rectangles on the right side of the display by $0.08° \pm 0.07°$ (95% CI: -0.074 – 0.193). A paired-sample t-test comparing the magnitude of the ARE for the left and right cue sides showed no difference in the magnitude of the ARE, $t(14) = 0.95$, $p = 0.36$, $d = 0.25$. Additionally, one-sample tests showed that the magnitude of the ARE was significantly greater than zero for the left cue, $t(14) = 7.98$, $p < 0.001$, $d = 2.06$. However, the ARE was not found to be greater than zero for the right cue, $t(14) = 1.24$, $p = 0.24$, $d = 0.32$. Interestingly, one participant drove the lack of a significant ARE for the right cue. This outlier participant had a baseline asymmetry that was six times greater than the mean asymmetry for the group with a difference in $Right_{PSE} - Left_{PSE} = -0.64°$ compared to the group mean of $-0.10° \pm 0.06°$ in the no- cue condition. Re-running the above analyses excluding this one participant showed that results parallel those observed for width judgments with significant ARE effects for both the left and right cues and no difference in the magnitude of the distortion across the two cue sides (right vs. left ARE: $t(13) = 0.11$, $p = 0.91$, $d = 0.03$; left cue ARE: $\times =0.146°$ (95% CI: 0.110–0.184), $t(13) = 7.52$, $p < 0.001$, $d = 2.09$; right cue ARE: $\times =0.143°$ (95% CI: 0.090–0.152), $t(13) = 4.19$, $p = 0.001$, $d = 1.12$). Given the large baseline asymmetry in this participant, it is possible given the limited testing range used in the present study that the measurable effect of the cues would be negligible for this individual.

Next, the magnitude of the ARE was compared across width and height judgment groups to determine if the size of the distortion varied as a function of the measured dimension (perceived width vs. perceived height). A 2 ARE Side (left/right) × 2 Task Type mixed-design ANOVA was calculated with Task Type as a between-subject factor. Results show no main effect of ARE Side, $F(1,29) = 0.887$, $p = 0.35$, $\eta^2 = 0.030$, and no main effect of Task Type, $F(1,29) = 0.026$, $p = 0.873$, $\eta^2 = 0.001$. There was also no ARE Side × Task Type interaction, $F(1,29) = 0.238$, $p = 0.629$, $\eta^2 = 0.008$, indicating no difference in the ARE magnitude across the width and height judgments.

Discussion

There are three main findings from the present experiment. First, we found evidence that the involuntary cues increased the perceived size of the target rectangle not only along the direction of the horizontal attentional shift from fixation out toward a peripheral cue (i.e., perceived width), consistent with the standard ARE, but also along the orthogonal dimension (i.e., perceived height). Second, we found that the magnitude of this distortion was equivalent for the width and height judgments, supporting the hypothesis that distortions of equal magnitude would be observed around the location of the cue. Finally, in the no-cue condition we observed differential baseline asymmetries in the perceived width and height of rectangles on the left and right side of the space.

Regarding the first two findings, the results show that when either the left or right comparison rectangles were cued, smaller PSEs were observed than in the no-cue condition. The reduction in PSEs is consistent with a perceived expansion in the perceived height or width of the rectangles relative to the no-cue condition. That is, the larger the perceived expansion along a given dimension, the smaller the physical width or height of the comparison rectangle needed to be in order to be perceived as equivalent to the standard rectangle. This resulted in the significant Cue Side × Comparison Side interactions observed for both the width and height judgment groups. Additionally, the cues served to alter the difference in PSEs across the left and right comparison rectangles in similar ways. As seen in Figs. 4b and 4d, compared to the baseline asymmetries in the perceived size of the left and right comparison rectangles in the no-cue condition, cueing the left or right side of space increased the perceived width or height of the rectangle on the cued side by ~0.10° on average. Additional analyses showed no statistical difference in the magnitude of this distortion across the left and right cue conditions. This suggests a symmetrical, consistent expansion in perceived size regardless of the hemifield of presentation.

As seen in Fig. 1, all previous ARE studies have investigated shifts in position or shape along one radial direction (i.e., from fixation out to the cue location). The present study therefore utilized an important novel design manipulation that assessed whether changes in perceived shape occur symmetrically around the cued location by testing dimensions that were both parallel and orthogonal to the direction of the attention shift. The results of this experiment provide clear evidence for a symmetrical distortion that is equivalent along the width and height dimensions of the cued rectangle. This was seen in the lack of a three-way interaction for the overall analysis of PSEs across the two task types (width and height judgments). Additionally, results show no ARE Side × Task Type interaction, again supporting that the magnitude of the distortion did not differ across the width and height dimensions. While one is limited in the inferences that can be made from the lack of statistical effects, it is important to note that the symmetrical distortion hypothesis predicts both that a significant ARE will be found along the orthogonal dimension and that it will be equivalent in magnitude to the ARE along the parallel dimension. The fact that both of these predictions were supported by the data provides support for a localized, symmetrical distortion surrounding the location of the cue rather than a directional distortion that only occurs along the dimension of the attentional shift. Based on the available neurophysiological literature on the spatial distribution of receptive field changes around peripherally attended locations (Connor et al., 1996), these results provide support for the hypothesis that the ARE is driven by localized distortions in the metric coding of visual space as proposed by Suzuki and Cavanagh (1997).

An additional finding from Experiment 1 regards some global differences in perceived width and height judgments. The PSE analyses showed an overall Comparison Side × Task Type interaction effect. As seen in Fig. 4, for the width judgments we found smaller PSEs when the comparison rectangle was on the left side of the display in the no-cue condition. As noted in the introduction to the experiment, smaller PSEs are consistent with participants perceiving the rectangle on the left side of the display as wider than the rectangle on the right side of the display. This is due to perceptual expansions of one rectangle requiring physical reductions in size in order for the two rectangles to be perceived as physically equivalent, as measured by the PSE. This baseline difference of rectangles appearing relatively wider on the left side of the display is consistent with the standard *psuedoneglect* phenomenon seen using variants of the bisection task (Jewell & McCourt, 2000; McCourt & Jewell, 1999; Porac, Searleman, & Karagiannakis, 2006; Rueckert, Deravanesian, Baboorian, Lacalamita, & Repplinger, 2002), localization tasks (Fortenbaugh, VanVleet, Silver, Robertson, 2015b), and a variant of the relative size judgment task that used oval shapes for target stimuli (Charles et al., 2007). In the study by Charles et al. (2007), filled white ovals presented on a gray background were perceived as wider (i.e., with smaller measured PSEs) when they were presented on the left side of a display compared to the right side. In this study the standard target was a 3° × 3° oval (i.e., circle) and the oval stimuli were centered at 5° eccentricity on either side of fixation. The mean error in PSE was -0.03° and +0.04° for the left and right comparison ovals, respectively. In the present study, the inner edge of the rectangles was fixed at 5° eccentricity in order to prevent participants from strategically basing their size judgments on "bisecting" the gap between the inner edges and the fixation point, as this could be used to infer size from the relative distances from fixation. That is, a potential confound with fixing location based on the center of the stimuli is that stimuli could be judged as wider/thinner if the gap between the inner edge and fixation was closer/farther, with the inner edge of thinner rectangles being farther from fixation than wider rectangles if the rectangles are centered at a fixed eccentricity. Regardless of this change in design, however, we find very similar baseline errors with mean errors in the PSE of -0.027° and +0.046° for the left and right comparison rectangles, respectively. In the study by Charles et al. (2007), assessments of baseline asymmetries in the perceived height of the ovals were also assessed and showed no difference in the PSE for comparison ovals on the left and right side of the display for their stimulus configuration. However, the Comparison Side × Task Type interaction in the current experiment suggests an overall different pattern for the height judgments, where participants on average perceived the left comparison rectangle as shorter than the right comparison rectangle. As the current study was not specifically designed to focus on pseudoneglect effects, the extent to which this pattern of wider and shorter for rectangles on the left reflects a general pattern, is stimulus specific (i.e., ovals vs. rectangles), or reflects specific participant sample characteristics that would not replicate in additional samples of participants, is an area for future research.

Experiment 2

The results thus far are consistent with brief pre-cues leading to transient distortions in the underlying representation of visual space around the cued location. However, if the results of the previous experiment are due to distortions in the underlying metric of visual space rather than a distortion that is specific to object shape and size perception, then it should also be possible to observe distortions in location perception by changing the response judgment required of the participants. Experiment 2 was therefore designed to test this hypothesis by varying cue position within the boundaries of one of the two rectangles and using the method of constant stimuli to measure the extent to which changes in relative cue position alters the perceived distance of the cued rectangle from fixation. If the locus of the spatial distortion varies with the relative position of the cue within one of the rectangles, then shifting the cue closer to fixation was predicted to repel the inner boundary of the cued rectangle closer to fixation, leading participants to see the cued rectangle as being shifted closer to fixation, consistent with the distortions in relative position seen in the standard ARE paradigm.

Methods

Participants

A new cohort of 13 participants (eight females; mean age = 25.9 ± 5.3 years) completed the experiment. Two participants reported being left-handed and all participants had normal or corrected-to-normal vision. One participant experienced ocular discomfort during the experiment and examination of this participant's data showed two conditions where response patterns did not cross the 50% proportion (i.e., responses did not vary systematically with changes in the actual width of the comparison rectangle). As such, data from this participant could not be used to estimate a corresponding psychometric function and PSE without extrapolation and the participant was therefore excluded from analyses.

Materials and procedure

This experiment was conducted on a 15-in. MacBook Pro (refresh rate = 60 Hz; resolution: 1,440 × 900 pixels). Stimuli were generated using Matlab (Mathworks Inc.,

Natick, MA, USA) and the Psychtoolbox extension (Brainard, 1997; Pelli, 1997). Before beginning the experiment, the distance and height of the monitor was adjusted to allow for comfortable viewing and posture at a constant distance of 50 cm from screen to eyes. The stimulus display was similar to Experiment 1. However, rather than having participants determine stimulus sizes, this experiment asked participants to judge which of the two rectangles was closer to the red fixation cross (0.5° × 0.5°) in the center of the screen.

The stimulus presentation sequence followed that of Experiment 1 (see Fig. 2). Each trial began with a blank screen for 1,000 ms followed by a tone and white cue that lasted 50 ms. This preceded a 100-ms ISI where only the fixation cross was presented and then the two rectangles were presented on either side of fixation for 100 ms. After the rectangles disappeared, the screen went entirely blank until a response was recorded.

As in the previous experiment, the stimuli consisted of a white pre-cue (1.0° × 1.0°) and the standard rectangle was a perfect square (3.0° × 3.0°). In contrast to the previous experiment, however, the comparison rectangle was also always a perfect square (3.0° × 3.0°) and the horizontal offset of the comparison rectangle from fixation was varied (see Fig. 5) with no vertical offset. That is, on each trial, the inner edge of the standard rectangle appeared at 5.0° eccentricity from the fixation cross and the side on which the standard rectangle appeared (left/right) varied across trials. In contrast, lateral offset of the comparison rectangle varied such that the foveal edge was located at one of seven eccentricities (3.5°, 4.5°, 4.75°, 5°, 5.25°, 5.5°, and 6.5°). In this experiment there were also three potential cue locations: horizontally offset foveally (-0.75°), centered, or offset peripherally (+0.75°) within the comparison rectangle (see Fig. 5 for relative locations). As the focus of this experiment was relative changes in perceived location as a function of cue position, and in order to keep the total number of trials to a reasonable level, the cue was
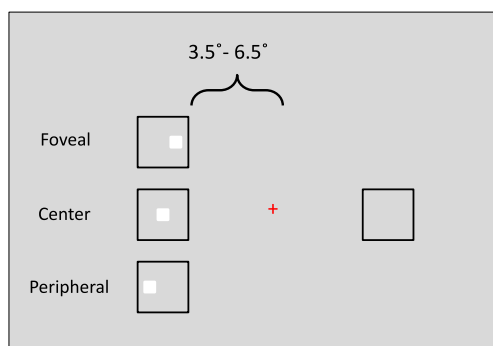
Fig. 5 Schematic of Experiment 2 illustrating the three relative cue locations within the comparison rectangle. The comparison rectangle was horizontally offset from fixation at one of seven eccentricities while the standard rectangle's position was fixed with the inner edge at 5° eccentricity. Stimulus presentation timing was the same as Experiment 1

always presented on the same side as the comparison rectangle. Across the two comparison sides (left/right), seven comparison rectangle eccentricities, and three cue shifts within the comparison rectangle (peripheral, centered, foveal), each of the 42 conditions was randomly repeated seven times in a block of trials.

Similar to the previous experiment, trials were completed in two blocks, one asking participants to judge which rectangle was closer to fixation and the other asking participants to judge which one was farther. In contrast to Experiment 1, responses were recorded using the left and right mouse buttons rather than the left and right arrow keys. The use of a mouse allowed the vertical height of the laptop to be raised, allowing for participants to view the stimuli directly ahead while comfortably positioned in a chinrest. Participants pressed the left mouse button to select the rectangle on the left side of the display and the right mouse button to select the rectangle on the right side of the display. As before, block order was alternated such that half the participants completed the experiment in the Close-Far block order and half completed the Far-Close block order. Ten practice trials with feedback were completed at the beginning of each block and each block consisted of 294 trials (for a total of 588 trials across the entire experiment).

Results

As in the previous experiment, the responses for the block with closer judgments were flipped and combined with the block of farther judgments, resulting in 42 total combinations across the 2 Comparison Sides, 3 Cue Shift conditions, and 7 Comparison Eccentricities. The proportion of trials that participants responded that the comparison rectangle was farther from fixation was determined for each of the seven comparison eccentricities tested. Cumulative Gaussian functions were then fit to the data (GraphPad Prism; GraphPad Software, Inc) to determine the PSE. In this experiment, the PSE represents how far offset the comparison rectangle needed to be (in degrees of visual angle from fixation) for it to be perceived as equivalent to the standard rectangle, whose inner edge was always fixed at 5° from fixation (see Fig. 6a for group-level means).

A 2 (Comparison Side) × 3 (Cue Shift) repeated-measures ANOVA was calculated on the PSEs. As seen in Fig. 6b, overall differences were seen in the relative position of the left and right comparison rectangles, as reflected in the main effect of Comparison Side, $F(1,11) = 7.566$, $p = 0.019$, $\eta^2 = 0.408$. That is, participants tended to perceive the comparison rectangle as farther away when it was presented on the left side of the screen than when it was presented at the same eccentricity on the right, leading to smaller overall PSE values when the comparison rectangle was on the left side of the display.

(a)

(b)
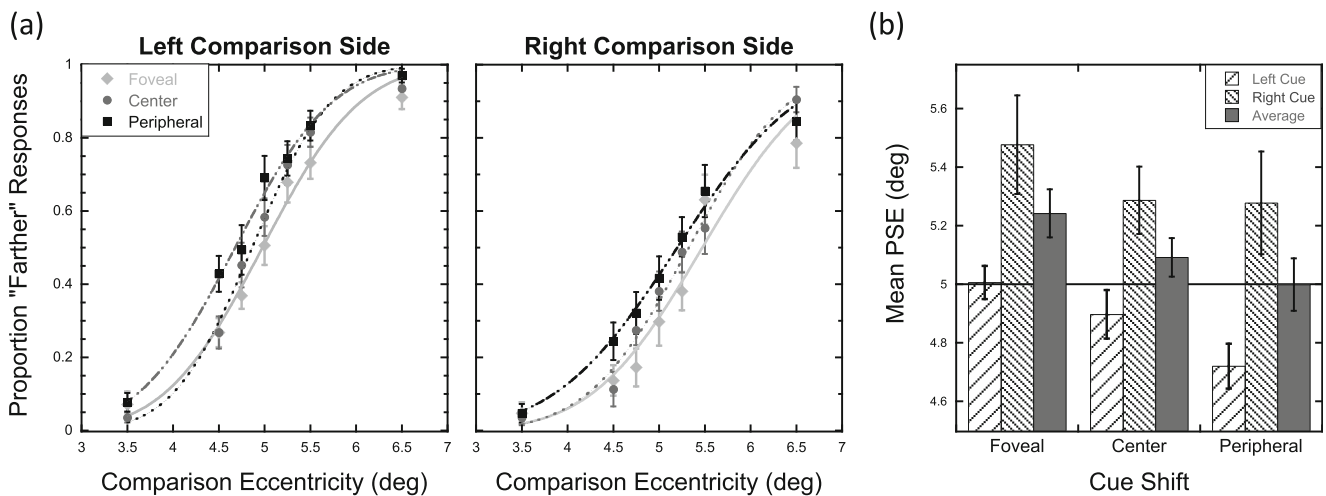
Fig. 6 Experiment 2 group means and points of subjective equality. (**a**) Plots show the mean proportion of time participants responded that the comparison rectangle was farther from fixation than the standard rectangle for the seven comparison offsets tested as a function of which side the comparison rectangle was on (left/right) and the location of the cue (foveal/center/peripheral). Curves show the best fitting cumulative Gaussian function for the group means. (**b**) Bar graph showing the mean PSE for the comparison rectangle as a function of cue location and the relative side of the comparison rectangle. The average PSE collapsed across comparison side is also shown. The solid horizontal line show the expected PSE if no distortion were present given that the standard rectangle was always offset from fixation by 5.0°. All error bars show ±1 SEM

As predicted for this experiment, Fig. 6b also shows significant changes in the PSEs across the three different Cue Shift conditions, $F(2,22) = 5.051$, $p = 0.016$, $\eta^2 = 0.315$. Namely, as the cue moved from the more peripheral to the foveal interior of the comparison rectangle, there is a monotonic increase in the PSEs, consistent with the comparison rectangle appearing closer and closer to fixation and thus requiring its physical location to be moved farther and farther out from fixation (i.e., a repulsion of the inner contour toward fixation). While numerically there are differences in the PSEs for the three cue shift conditions across the left and right side of space, there was not a significant Cue Side × Cue Condition interaction $F(2,22) = 1.310$, $p = 0.290$, $\eta^2 = 0.106$. This suggests that the relative magnitude of the repulsion due to the changes in the cue position were equivalent for the left and right comparison rectangles.

Discussion

There are two main findings from this experiment. First, as predicted, we found that PSEs increase the closer the cue was placed to the foveal edge of the stimulus. That is, the more foveally the cue was presented within the comparison rectangle, the closer to fixation the comparison rectangle appeared. This is predicted by the ARE because repulsion of the interior edge towards fixation by the foveal cue condition should push the perceived location of the cued stimulus towards fixation in a way that elongates perception of the rectangle inward toward fixation. Second, a main effect of Comparison Side was observed, with comparison rectangles on the left side of the display generally being perceived as farther from fixation than

the same rectangle on the right side of the display, leading to smaller PSEs for the left comparison rectangles overall. Interestingly, there was no Comparison Side × Cue Condition interaction, indicating that there was no significant asymmetry in ARE magnitude between the right and left hemifields.

The main effect of Cue Shift condition is consistent with the hypothesis laid out by Suzuki and Cavanagh (1997) that the ARE reflects a distortion in the underlying metric of visual space due to changes in receptive field properties in retinotopic early visual cortex. While these experiments cannot dissociate between the three potential mechanisms that were proposed (shrinking, tuning, shifting of classical receptive fields), the current results provide new insights that support a transient warping or distortion of visual space that is due to the cues. To date, all studies of the ARE effect have only assessed one spatial dimension within a given study: either perceived position (Chien, Ono, & Watanabe, 2011; DiGiacomo & Pratt, 2012; Gozli & Pratt, 2012; Kosovicheva et al., 2010; Pratt & Arnott, 2008; Pratt & Turk-Browne, 2003; Suzuki & Cavanagh, 1997) or perceived shape (Fortenbaugh et al., 2011; Toba et al., 2011). Using the same stimuli as Experiment 1 but changing the relative cue-rectangle positions and the type of judgment required, we have now shown that it is possible to observe not only shifts or "repulsions" in the perceived location of cued objects, but also symmetrical distortions in perceived height and width of cued objects. This suggests a general underlying mechanism may be driving these distortions in perceived object shape and relative location, consistent with a distortion in the underlying metric of visual space. Of note, it is possible that cueing within the

rectangle at various locations altered both aspects simultaneously. That is, moving the cue foveally could have both altered the perceived width of the rectangle (i.e., elongating the width toward fixation), the overall position of the rectangle (i.e., a pure shift of the rectangle toward fixation without altering its width), or both simultaneously. It is not possible within the current design to disentangle these factors. However, we note that no participant ever reported the cued rectangle appearing "broken," even though the cue was placed quite close to the edge without overlapping with it (i.e., with a 0.25° gap between the edge of the cue and the rectangle contour). This is consistent with the authors' own phenomenological experience of the effect, suggesting that regardless of the type of underlying distortion that drove the change in perceived distance from fixation, the distortion operated globally on the entire comparison rectangle and not only on one contour independently. Given that only three cue positions were tested, however, future work examining a larger range of cue position offsets may be able to test whether a similar pre-cue configuration has the capacity to "break" the continuity of the rectangle stimuli.

In addition to the overall changes in perceived distance as a function of the cue position, an overall main effect of comparison side was observed. Namely, independent of the cue position, participants tended to perceive the comparison rectangle on the left as farther from fixation than the same rectangle on the right side of the display, leading to smaller PSEs overall for the left comparison rectangles. At first this result seems contradictory to the pseudoneglect literature that the left halves of lines are perceived as longer than the right halves of lines, and our finding from Experiment 1 that the rectangle on the left appeared wider than the rectangle on the right. However, the instructions of the current experiment asked participants to judge how close each rectangle was from fixation. In this case, it was not necessary to consider the size of the rectangles but rather one only needed to assess the distance from the inner edge of the two rectangles to fixation, which would be most similar to a gap detection task. If a physically equivalent gap distance between the fixation point and the inner edge of the left rectangle was perceived as longer than the corresponding distance on the right, this would lead to smaller PSEs for the left rectangles overall, consistent with the results of gap detection findings in the pseudoneglect literature (Bradshaw, Bradshaw, Nathan, Nettleton, & Wilson, 1986). There are several factors that limit the interpretation of the overall comparison side findings in the present study. First, as the study was designed to focus on the relative position of the cues, all possible combinations of Cue Side × Comparison Side conditions were not included. Additionally, no baseline no-cue condition was included. These conditions were not included due to time constraints. Thus, additional studies including baseline no-cue conditions would be needed in future studies assessing perceived distance from fixation to help validate that the current results are consistent with previous results in the pseudoneglect literature.

At this point we must ask ourselves, are there any other effects that could plausibly explain our results? Perhaps our participants' gazes were repeatedly drawn to the location of the cue and the stimuli looked bigger because they were magnified by the high cone density of the fovea. While the cue-rectangle SOAs were kept at 150 ms to help prevent any potential overt eye-movements (Findlay, 1981), the total duration from the onset of the cues to the offset of the rectangles was 250 ms. With time intervals of this length it is possible that on some proportion of trials participants were able make overt eye movements, namely express saccades (Fischer & Ramsperger, 1984). It is well established that there is a coupling between covert shifts of attention and saccades toward attended locations (Kowler, 1995; Peterson, Kramer, & Irwin, 2004). A limitation of the current study is that it does not include eye-movement tracking. Additionally, there is an important difference in the type of cue used in the present study versus the cue types that are typically used in ARE designs (see Fig. 1). Namely, the present study only used a single cue that was laterally offset to the left or right of fixation. This is in contrast to typical ARE studies, which use bilateral cues that are symmetrically offset in opposing visual quadrants (Fortenbaugh et al., 2011; Kosovicheva et al., 2010; Suzuki & Cavanagh, 1997). While Suzuki and Cavanagh (1997) included a single cue condition in two of their experiments, it is important to note that their study utilized small numbers of observers. Indeed, the same observers were included across multiple experiments, thus suggesting they were trained psychophysical observers. In contrast, the present study used samples of naïve undergraduate volunteers with little to no experience in psychophysical experiments or training in maintaining fixation. The use of the single, lateral cue in the present study therefore raises the potential issue of eye movements toward the cued location. While all participants were asked to maintain fixation at the center of the screen where the fixation cross was presented and the stimulus timing within trials was designed to help prevent overt saccades toward the cued location, active fixation also does not eliminate the presence of microsaccades. Though these types of small ballistic eye movements are involuntary, studies of their dynamics suggests that they occur at a rate of approximately 1/s to 1.5/s (Rolfs, Kliegl, & Engbert, 2008). While microsaccadic inhibition, or reductions in the rate of microsaccades, have been observed in the 100- to 300-ms time window after a peripheral stimulus onset (Engbert & Kliegl, 2003; Rolfs et al., 2008), this reduction does not correspond to a complete elimination of microsaccades after stimulus onset. Importantly, recent studies have also suggested a coupling between microsaccadic eye movements toward an involuntary cue location and resulting cueing effects on reaction time and perception (Engbert & Kliegl, 2003; Hafed, 2013; Hafed, Chen, &

Tian, 2015; Yuval-Greenberg, Merriam, & Heeger, 2014). If systematic eye movements (i.e., express saccades) or microsaccades were made toward the cued location on some proportion of the trials, this could potentially bring the cued rectangle closer to fixation than the non-cued rectangle before the offset of the rectangle stimuli. We therefore designed the final experiment to test whether physically shifting the location of one of the rectangles to be centered over fixation would lead to similar changes in the perceived width of that rectangle as was observed in Experiment 1.

Experiment 3

Participants in the previous two experiments were instructed to maintain fixation at the center of the screen where the fixation cross was presented on each trial. However, as no eye-tracking was completed it is possible that some participants made overt saccades or microsaccades toward the locations of the lateralized cue on some proportion of trials in the 250-ms interval between cue onset and rectangle offset (Engbert & Kliegl, 2003; Fischer & Ramsperger, 1984). Given the known bias for eye movements to be made toward the direction of a cue, these potential shifts would alter the retinotopic location of the rectangles, bringing the cued rectangle to fixation while the uncued rectangle would be presented further in the periphery. This raises the question of whether the distortions in perceived shape or location observed in the previous experiments can be explained by potential shifts of the cued rectangle toward the fovea. Adjusting the design used in Experiment 1, the final experiment therefore tested whether shifting the location of one of the rectangles to a more foveal location would make that rectangle appear wider than the same rectangle presented in the periphery. By eliminating the cue stimuli and only presenting pairs of rectangles centered or offset within the display, the duration that stimuli (excluding the initial fixation cross) were presented in each trial was reduced from 250ms to 100ms. This greatly reduced the probability that overt eye movements or microsaccades could be executed and completed before the offset of the rectangle pairs (Engbert & Kliegl, 2003; Findlay, 1981; Fischer & Ramsperger, 1984).

Methods

Participants

This experiment used a within-subjects design with a new cohort of 16 naïve participants (eight females; mean age = 21.06 ± 2.74 years). As in Experiment 1, all participants reported being right-handed and having normal or corrected-to-normal vision.

Materials and procedure

Experiment 3 used the same experimental design as Experiment 1 (see Fig. 2) except for the following changes: (1) there was no white cue in the second display screen when the tone sounded for 50 ms; (2) the fixation cross was removed from the fourth and fifth display screens (i.e., when the two rectangles were shown for 100 ms and during the response screen). This was done to accommodate conditions where the standard rectangle was presented at fixation. This experiment primarily compared changes in perceived width for balanced rectangle presentations (one on each side of fixation) used in the previous experiments, to laterally shifted presentations where the standard rectangle was centered over fixation. (3) As in the previous experiments, the standard rectangle was always 3.0° × 3.0° but here the distance between the two rectangles was reduced to a total of 5° offset between stimuli. In the "peripheral offset" conditions, which replicated the balanced rectangle distribution from Experiments 1 and 2, the inside edges of the standard rectangle and the comparison rectangle were equidistant from the fixation cross at 2.5° on either side. In the "foveal offset" conditions, the standard rectangle was always centered at fixation while the comparison rectangle was presented to the left or right side, again keeping a 5° inner edge separation with the inner edge of the comparison rectangle now appearing at 6.5° eccentricity from fixation. Like the width task in Experiment 1, Experiment 3 required participants to make relative width judgments and tested the same seven comparison width sizes (2.6°, 2.8°, 2.9°, 3.0°, 3.1°, 3.2°, and 3.4°). As no cues were used in this experiment, following the methodology of Charles et al. (2007) participants were always asked to judge which of the two rectangles appeared wider. With the 2 Comparison Sides × 2 Offsets × 7 Comparison Sizes repeated-measures design, there were 20 repeats across the 28 conditions, for a total of 560 trials. The experimental block was broken up into five separate blocks with four breaks. As in the previous experiments, participants were given ten practice trials before beginning experimental trials to familiarize themselves with the task and response necessary.

Results

The proportion of the trials that participants responded that the comparison rectangle was wider than the standard was determined for each of the seven comparison widths tested across the four experimental conditions. Cumulative Gaussian functions were then fit to the data (GraphPad Prism; GraphPad Software, Inc) to determine the PSE. The PSE in this experiment represents the average width of the comparison rectangle that is seen as equal to the width of the standard rectangle (3.0°) in each of the four main conditions of interest (Fig. 7a displays group-level means).

(a)

(b)
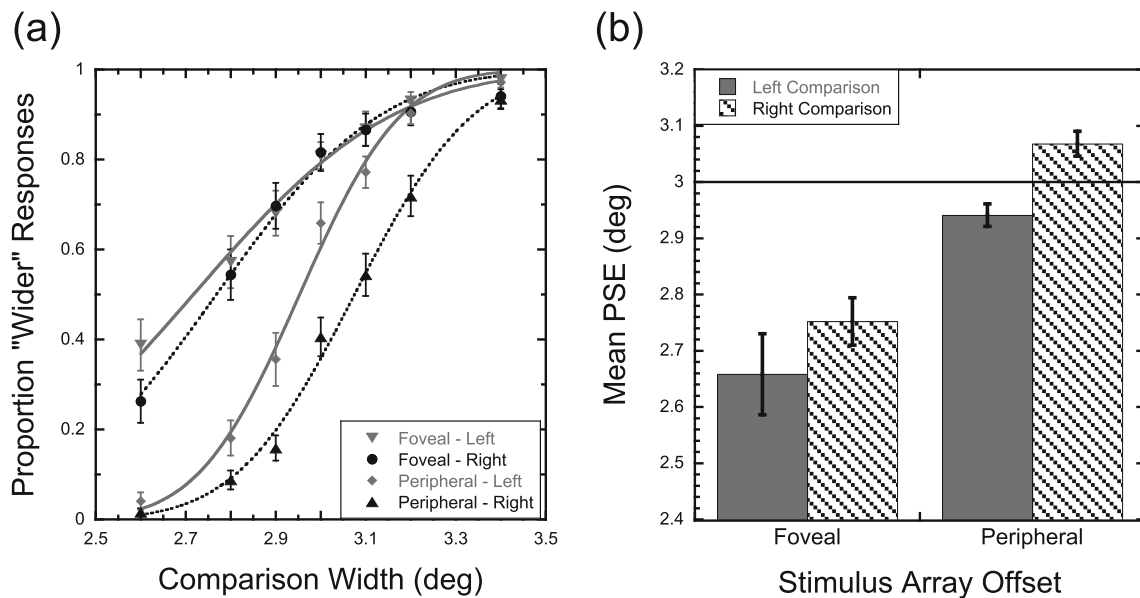
Fig. 7 Experiment 3 group means and PSE. (**a**) Plot shows the mean proportion of time participants responded that the comparison rectangle was wider than the standard rectangle at the seven comparison widths. Width means are shown as a function of which side the comparison rectangle was located (left/right) and the trial stimulus array offset position (foveal/peripheral). Curves show the best fitting cumulative Gaussian function for the group means. (**b**) Bar graph showing the mean PSE for the comparison rectangle width as a function of the comparison rectangle location and the stimulus array offset position (i.e., position of the standard rectangle at fixation or periphery). The solid horizontal line shows the expected PSE if no distortion were present given that the standard rectangle always had a width of 3.0°. All error bars show ± 1 SEM

A 2 (Comparison Side) × 2 (Rectangle Offset) repeated-measures ANOVA was calculated on the PSEs. As seen in Fig. 7b, stimuli on the left side of space were consistently seen as bigger (resulting in smaller PSEs) than their rightward counterparts. This is reflected in the significant main effect of Comparison Side, $F(1,15) = 7.851$, $p = 0.013$, $\eta^2 = 0.344$. In addition to this baseline asymmetry, the main effect of interest was Rectangle Offset, which was also significant, $F(1,15) = 36.231$, $p < 0.001$, $\eta^2 = 0.707$. This can also be seen in Fig. 7b, where comparison rectangles on both the left and right were perceived as substantially bigger (resulting in lower PSEs) when the standard rectangle was presented at fixation. This indicates that rectangles presented in the visual periphery appeared larger than the same rectangles presented at fixation. The lack of an interaction between Rectangle Offset and Comparison Side, $F(1,15) = 0.307$, $p = 0.588$, $\eta^2 = 0.020$, indicates that the Comparison Side and Rectangle Offset effects are independent and potentially additive (as seen in Fig. 7b).

Magnitude of pseudoneglect across experiments As a final analysis, we examined the magnitude of the intrinsic left-right size asymmetries in perceived width across Experiment 1 and the peripheral offset condition of Experiment 3. We therefore ran a 2 Comparison Side × 2 Experiment mixed-design ANOVA, with the Experiment group as a between-subjects factor. Results show a main effect of Comparison Side, $F(1,30) = 13.196$, $p = 0.001$, $\eta^2 = 0.305$, with PSEs significantly smaller for the left comparison rectangle than the right

comparison rectangle. There was no main effect of Experiment, $F(1,30) = 0.407$, $p = 0.528$, $\eta^2 = 0.013$, and no Comparison Side × Experiment interaction, $F(1,30) = 1.047$, $p = 0.314$, $\eta^2 = 0.034$. Collapsing participants across the two experiments (see Fig. 8), we find a significant correlation across the left and right comparison PSEs, $r = -0.841$, $p < 0.001$, resulting in a medium overall effect size for paired-samples of $d = 0.641$. Collectively these results demonstrate a tendency for participants to perceive the rectangle on the left side of space as wider than the same rectangle presented on the right side of space, with the degree of asymmetry showing consistency across experiments in the baseline, no-cue condition.

Discussion

The results of this experiment demonstrate that when the same rectangle is presented at fixation, it appeared smaller than the same sized rectangle presented in the periphery. This final experiment therefore provides support that changes in perceived shape and location across Experiments 1 and 2 cannot be explained by systematic eye-movements toward the cued location. That is because eye movements toward the cued location would bring that rectangle in toward fixation while the non-cued rectangle is moved further into the visual periphery. In light of this, the results of Experiment 3 suggest that the cued rectangle would appear thinner, rather than wider as was observed in Experiment 1. Thus, the results of Experiment 3 indicate that any potential eye-movements bringing the cued

(a)

y = 5.73 - 0.91x R^2 = 0.707

(b)
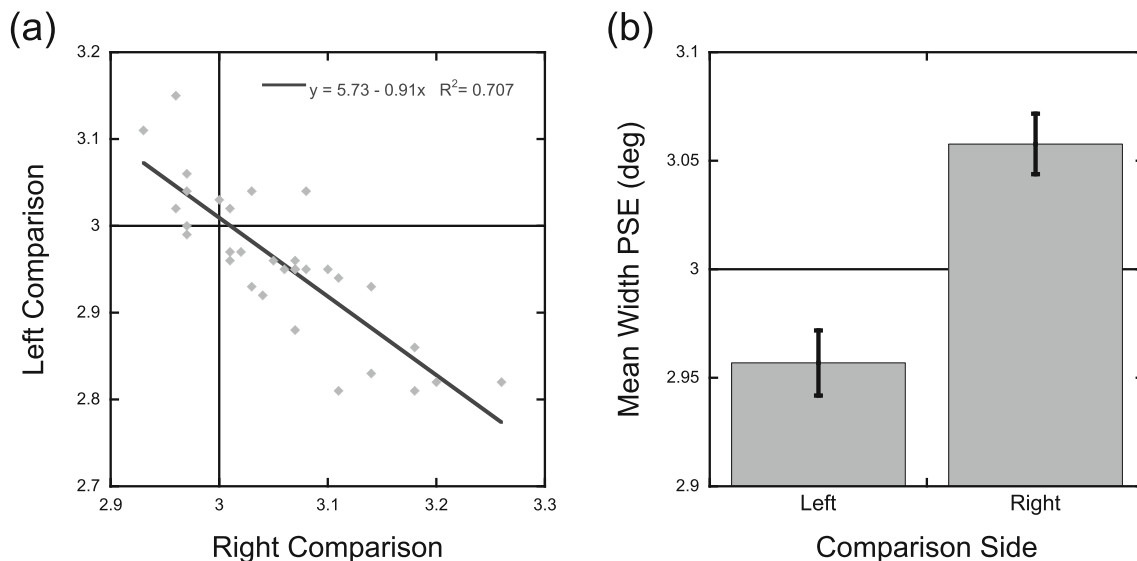
Fig. 8 Left-right size asymmetry in perceived width for the no-cue conditions collapsed across Experiments 1 and 3. (**a**) Scatterplot shows the PSE for the left comparison rectangle as a function of the corresponding PSE of the right comparison rectangle. Each diamond represents a single participant. (**b**) Bar graph shows the mean PSE for the comparison rectangle width as a function of comparison side (left/right) across all participants. The solid horizontal line at 3.0° show the expected PSE if no distortion were present. Error bars show ±1 SEM

rectangle closer to fixation in Experiments 1 and 2 would likely have only served to underestimate the ARE.

At least one recent study has found that the perceived sizes of stimuli diminish as they are shifted further out to the periphery (Baldwin, Burleigh, Pepperell, & Ruta, 2016). However, this study used relatively low luminance stimuli and contrast levels compared to the current study. A study by Bedell and Johnson (1984) found that the luminance of a stimulus determines the perceived change in size. According to Bedell and Johnson, peripheral stimuli are seen as larger, especially along the width dimension, under high luminance conditions and smaller under low luminance conditions. They propose that this relationship between luminance and the perceived size of peripheral stimuli can be explained by (1) peripheral stimuli activating more retinal photoreceptors with above-threshold brightness and (2) peripheral retinal ganglion cells' pooled visual fields that summate detected luminance over comparatively larger receptive fields than in the fovea. Thus, while the size perception literature has inconsistent findings, there is evidence to suggest that the current findings are consistent with previous size disparities observed as a function of retinal location.

In addition to the foveal-peripheral distinction, the same left-right asymmetry was observed across both Rectangle Offset conditions. Analyses comparing the degree of left-right asymmetry showed no overall difference across the two samples of participants in Experiments 1 and 3, with a strong bias overall to perceive a rectangle as wider when it was shown on the left side of the display compared to the right side. While pseudoneglect has been extensively studied using midpoint judgments of single lines or objects (Benwell, Thut, Learmonth, & Harvey, 2013; Darling, Logie, & Della Sala,

2012; Hurwitz, Valadao, & Danckert, 2011; Jewell & McCourt, 2000; Luh, 1995; McCourt, Garlinghouse, & Slater, 2000; McCourt & Jewell, 1999; McCourt & Olafson, 1997; Nicholls, Hughes, Mattingley, & Bradshaw, 2004; Nielsen, Intriligator, & Barton, 1999; Orr & Nicholls, 2005; Rueckert et al., 2002; Toba et al., 2011), to our knowledge assessments of size and shape asymmetries across multiple objects have received far less attention with the study by Charles et al. (2007) being an important exception. The present results support the pseudoneglect literature showing that pseudoneglect can be observed not only in the perceived midpoint of a line but also in relative width judgments (Charles et al., 2007), gap detection (Bradshaw et al., 1986), and gradient detection (Nicholls et al., 2004; Orr & Nicholls, 2005). The observation that both foveal-peripheral and left-right asymmetries could concurrently be measured in this design is also consistent with previous pseudoneglect findings when target objects are shifted to the left or right side of a display (Jewell & McCourt, 2000; Orr & Nicholls, 2005).

General discussion

The results of the present study extend previous research on the Attentional Repulsion Effect (ARE) (Suzuki & Cavanagh, 1997). Across three experiments, the present study has shown that briefly presented involuntary cues systematically alter both the perceived width and height of a rectangle presented at that location. This demonstrates for the first time that distortions are equivalent in both direction and magnitude for dimensions that are parallel and orthogonal to the radial direction of the attention shift. The second experiment

extended previous findings by showing that the same methodology used to assess distortions in perceived shape could also be used to manipulate perceived distance from fixation by simply shifting the position of the cues and the response type. These findings are consistent with the receptive field models proposed by Suzuki and Cavanagh (1997) in the original ARE paper and provide novel evidence that the distortion underlying the ARE involves a transient warping in the metric of visual space, thus impacting various aspects of spatial and object perception. Finally, the third experiment of this study demonstrates that equivalent rectangles appear wider when they are presented in the visual periphery compared to fixation. This control experiment suggests that the results of the previous two experiments are unlikely to be explained by overt eye movements or microsaccades. This is because eye movements, which would be directed toward the cued location (Hafed, 2013; Kowler, 1995; Peterson et al., 2004), would shift the cued rectangle toward fixation and lead to the cued rectangle appearing thinner than the un-cued rectangle. Collectively, these findings extend the previous ARE literature by providing evidence in support of a symmetric distortion radiating out from the location of an involuntary cue (see Fig. 1b, right panel). This suggests that the basis of the ARE is a general underlying distortion in the representation of visual space rather than a more specific distortion that only serves to repel contours along a single direction. That is, the ARE is more than simply a "repulsion" of vernier lines, it is an alteration in the metric of visual space that impacts the coding of distance, position, and object shape.

Comparing the magnitude of the ARE across studies Studies have used a variety of stimulus configurations and analytic tools to examine the ARE. A search of the literature on the attentional repulsion effect identified five previous studies (Chien et al., 2011; Fortenbaugh et al., 2011; Kosovicheva et al., 2010; Suzuki & Cavanagh, 1997; Toba et al., 2011) that used either adaptive threshold measures or the method of constant stimuli to calculate the PSE for individual participants (see Fig. 1 for configurations utilized in these studies). One notable aspect across these studies is the surprising level of invariance in the magnitude of the ARE. Across five studies spanning close to two decades, using varying computer monitors, participant groups, and varying stimulus configurations, the degree of variation in the magnitude of the ARE is quite small (ARE magnitudes of approximately 0.05° to 0.15°, with a range of ~0.1°). This consistency in the magnitude of the ARE suggests a robust spatial distortion induced by the involuntary cues. The similarity in the magnitude of the measured distortion across stimulus configurations and response judgment types, in conjunction with the results of Experiment 1 showing similar sizes of distortions across the width and height dimensions, supports the hypothesis that the ARE in all of these studies can be explained by an underlying

localized distortion in the representation of visual space. This common mechanism subsequently serves to alter one's perception across multiple spatial and object dimensions in a consistent manner. The similarity further highlights that the ARE provides an important paradigm that can be used to study how rapid, involuntary shifts in attentional focus alter one's perception of the external environment.

Several models were proposed by Suzuki and Cavanagh (1997) to explain the origin of the ARE including the shifting of receptive fields toward the cued location, surround suppression, and sharper tuning of receptive field widths. Such shifts in receptive field centers and tuning of receptive fields near attended locations have been found in a variety of extrastriate visual regions (Anton-Erxleben & Carrasco, 2013; Connor et al., 1996; Connor, Preddie, Gallant, & Van Essen, 1997; David, Hayden, Mazer, & Gallant, 2008; Moran & Desimone, 1985; Womelsdorf, Anton-Erxleben, & Treue, 2008). Given that photoreceptor and ganglion cell density decreases (Curcio & Allen, 1990; Curcio, Sloan, Packer, Hendrickson, & Kalina, 1987; Curcio, Sloan, Kalina, & Hendrickson, 1990) and receptive field sizes increase as a function of eccentricity across visual areas (Anton-Erxleben & Carrasco, 2013; Smith, Singh, Williams, & Greenlee, 2001; Wu, Yan, Zhang, Jin, & Guo, 2012), it seems likely that any model that involves changes to receptive field properties would vary as a function of eccentricity as well. Two previous studies have manipulated the distance from the cues to the vernier target stimuli (Kosovicheva et al., 2010; Suzuki & Cavanagh, 1997), with the results of Kosovicheva et al. (2010) supporting a decline in the magnitdue of the ARE as the cue moved into the periphery and the separation of the cues from the vernier lines increases beyond 4–6°. However, future studies of the ARE may benefit from additional within-subject comparisons of the magnitude of the ARE using paradigms that allow for manipulations of cue eccentricity to further characterize the relationship between ARE magnitude and cue eccentricity.

Left/right intrinsic size asymmetries Importantly, the impact of the cues served to modulate perceived shape or location in addition to the intrinsic size asymmetries across the left and right hemifields seen in the no-cue condition. That is, the ARE and baseline asymmetry in perceived width may be additive distortions, but at a minimum we found no evidence for an interaction across the two effects. This baseline size asymmetry in the no-cue conditions, where the same sized rectangle appears wider when it is presented on the left side of the display, is consistent with the pseudoneglect phenomenon found in line bisection tasks (Charles et al., 2007; Jewell & McCourt, 2000). In Experiment 1, the degree of change from the baseline condition was equivalent when the left and right sides of the displays were cued, suggesting that the ARE operated in addition to the participants' baseline degree of asymmetry (e.g., pseudoneglect). The results of Experiment 1 also suggest an

opposing baseline asymmetry along the height dimension, with rectangles on the left appearing shorter than rectangles on the right. However, this finding is inconsistent with the results of Charles et al. (2007), who found no left-right asymmetry along the height dimension. Given the sparsity of data measuring left-right asymmetries in perceived height, additional work is needed to determine how robust the height asymmetries we observed are across stimuli and individuals.

The fact that left-right asymmetries were observed in perceived width across Experiments 1 and 3 is interesting because pseudoneglect is thought to have an attentional basis (McCourt, Garlinghouse, & Reuter-Lorenz, 2005; Toba et al., 2011), similar to the ARE (Suzuki & Cavanagh, 1997). For pseudoneglect, one theoretical explanation is that the baseline distribution of voluntary attention is biased first toward the left side of stimuli or the left half of visual space given the evidence that attentional systems in humans are right-hemisphere lateralized (McCourt et al., 2005; Toba et al., 2011). Neuroimaging studies of various bisection tasks have confirmed a unique role for right hemisphere regions, namely, the right parietal cortex in completion of these tasks compared to control conditions (Cavezian, Valadao, Hurwitz, Saoud, & Danckert, 2012; Çiçek, Deouell, & Knight, 2009). While pseudoneglect may reflect an intrinsic bias in how voluntary attention is oriented across visual space, one outstanding question in the literature is the extent to which involuntary and voluntary attention are supported by the same or different neural mechanisms (Mangun, 1995; Peelen, Heslenfeld, & Theeuwes, 2004; Rosen et al., 1999). While the answer to this question is beyond the scope of the present paper, it is of interest to note that at least two previous studies of the ARE suggest that it results from an early modulation of visual space prior to or at the level of visual area V1 (DiGiacomo & Pratt, 2012; Pratt & Turk-Browne, 2003). Thus, the ARE and pseudoneglect may have differing neural loci. This suggests that future work utilizing paradigms that explore the interaction of voluntary and involuntary attention on space perception may provide unique insight into the neural basis of these processes beyond what can be assessed from reaction time measures in cueing paradigms. Such work also may be able to determine if the effects of pseudoneglect and the ARE distortion are additive in nature. Further investigation of these two phenomenon may also shed more light on whether general involuntary and voluntary attention mechanisms are truly separable and distinct or rather represent different manifestations of the same cognitive processes along a continuum of alertness (Anderson, 2011). Finally, Druker and Anderson (2010) found that involuntary cue discrimination is enhanced when cues appear in high probability areas within the visual field. In standard ARE paradigms, the cues always appear at fixed locations, though they may vary across visual hemifield or quadrant. Given the findings of Druker and Anderson, it is possible that the magnitude of the ARE could vary with learned cue probability. Future ARE paradigms may therefore benefit from varying cue and stimulus locations across the visual field to elucidate potential interactions between the ARE, cue/stimulus spatial probabilities, and intrinsic hemispheric asymmetries.

Limitations and future directions There are several limitations to the current study. First, in order to help isolate the impact of the cues on the perceived width and height of the rectangles, only one dimension of the comparison rectangle was varied. This means the overall area of the comparison rectangles co-varied with changes in its physical width/height. However, maintaining a constant area for the comparison rectangle would also mean that changes in the width would co-vary with changes in the height, producing a potential confound in which dimensions were used for judging rectangle sizes. The goal of the present study was to try to isolate judgments of width from judgments of height in Experiment 1. Thus, controlling the opposing dimension but not the overall area of the comparison rectangle seemed appropriate. However, future work may be needed to try to dissociate the impact of overall size/area differences across the two rectangles from changes along a single dimension. Second, in Experiment 1 the impact of the cues on perceived width and height were tested using a between-subjects design across distinct trials. Thus, the current design was not able to assess the extent to which changes in perceived width occurred simultaneously with changes in perceived height, or if the instructions to attend to one dimension primarily affected perception along that dimension (e.g., judgments of perceived width led to increases in perceived width of the cued rectangle with no change in perceived height). Future work that allows for measurements of both perceived width and height within a single trial are needed to determine the extent to which task instructions may affect perceived size globally or along a single dimension using these types of stimulus configurations. Finally, only two directions were tested in the present experiment (width/height). In order to fully assess whether perceptual distortions follow the spatial pattern predicted from receptive field changes, future work testing additional eccentricities and radial directions, perhaps using more complex shapes as targets or rotating the rectangle targets is needed. However, shape distortions and perceptual capabilities have been shown to vary as a function of radial direction in the visual field (Abrams, Nizam, & Carrasco, 2012; Baldwin et al., 2016; Fortenbaugh, Robertson, & Esterman, 2017; Fortenbaugh, Silver, & Robertson, 2015a; McCourt et al., 2000; Nicholls et al., 2004). These previous findings, for example, might predict that intrinsic distortions seen along the width and height dimensions in Experiment 1 might flip if the stimuli are presented along the vertical meridian (Baldwin et al., 2016; McCourt et al., 2000). Thus, a complete understanding of the impact of involuntary cues on perceived shape and

location will require taking into account potentially differing intrinsic asymmetries as a function of visual field location.

Concluding remarks In conclusion, the results of the present study extend previous findings by demonstrating that briefly presented cues that attract involuntary attention can systematically alter one's perception of visual space. The ARE leads to distortions not only in the perceived relative location of multiple objects, but also the size and shape of individual objects. There are many future questions that remain to be answered. These include the extent to which the neural mechanisms that drive the ARE are the same or different to those that drive other attention effects, including intrinsic asymmetries (e.g., pseudoneglect) in space perception across the left and right visual fields and distortions in perceived location associated with sustained voluntary attention (Fortenbaugh & Robertson, 2011; Fortenbaugh et al., 2015b; Fortenbaugh et al., 2017). While the ARE has been shown to be robust across multiple stimulus configurations, the degree to which the magnitude of the ARE varies as a function of cue eccentricity requires further study. An early locus for the ARE in V1 or extra striate cortex suggests that the magnitude of the distortion should be affected by properties that are intrinsic to these regions. Changes in receptive field size as a function of eccentricity is one known property of neurons in early visual areas and thus an area that deserves further study. Finally, while this study showed equivalent distortions along the width and height dimensions of the rectangle stimuli, all potential radial directions from the attention shift were not assessed. Future studies using different stimuli shapes and assessing more angles are needed to determine if the magnitude of the effect is completely uniform around the cue location. While there remains much to be learned, the results of the studies that have been completed thus far highlight the important role that involuntary attention can play in shaping one's perception.

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