Shifts of visuospatial attention do not cause the spatial distortions of the Roelofs effect

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When a visible frame is offset left or right of an observer's objective midline, subjective midline is pulled toward the frame's center, resulting in an illusion of perceived space known as the Roelofs effect. However, a large frame is not necessary to generate the effect—even a small peripheral stimulus is sufficient, raising the possibility that the effect would be brought about by any stimulus that draws attention away from the midline. To assess the relationship between attention and distortions of perceived space, we adopted a paradigm that included a spatial cue that attracted the participant's attention, and an occasional probe whose location was to be reported. If shifts of attention cause the Roelofs effect, the probe's perceived location should vary with the locus of attention. Exogenous attentional cues caused a Roelofs-like effect, but these cues created an asymmetry in the visual display that may have driven the effect directly. In contrast, there was no mislocation after endogenous cues that contained no asymmetry in the visual display. A final experiment used color-contingent attentional cues to eliminate the confound between cue location and asymmetry in the visual display, and provided a clear demonstration that the Roelofs effect is caused by an asymmetric visual display, independent of any shift of attention.

Introduction

When an observer makes a judgment about an object's orientation or location, contextual information from the visual scene is typically used to help refine the judgment (Asch & Witkin, 1948). However, if the contextual information contained within the scene is misleading, visual illusions can occur. In a classic example, Roelofs (1936) presented an observer with a large rectangular frame positioned so that one edge of the frame was aligned with the observer's objective midline. To the observers, though, this was not how it appeared: when asked to adjust the frame so that the edge was directly ahead, the observers shifted the frame even further in the direction of the offset. Roelofs' early experiments revealed that the presence of the large rectangular frame causes a distortion of the observer's subjective midline, with the midline biased in the direction of the offset frame (Brecher, Brecher, Kommerell, Sauter, & Sellerbeck, 1972; Brosgole, 1968; Werner, Wapner, & Bruell, 1953). A direct demonstration of this effect can be achieved by simply asking observers to point or make a saccadic eye movement to straight ahead in the presence of an offset frame. The observer's motor response typically deviates toward the center of the frame (Dassonville & Bala, 2004a; Dassonville, Bridgeman, Bala, Thiem, & Sampanes, 2004). In a recent adaptation of the classic Roelofs illusion, observers are asked to make a perceptual report of the location of a visual probe presented within the offset rectangular frame. The frame-induced distortion of subjective midline typically causes a systematic mislocalization of the probe as being displaced in a direction opposite the frame offset (i.e., the *induced* Roelofs effect; Bridgeman, Peery, & Anand, 1997; Dassonville & Bala, 2004a). For example, a right-shifted frame will cause a deviation of the subjective midline to the right, which, in turn, causes the enclosed target to appear to lie to the left of its actual location.

The primary focus of past research on the Roelofs illusion, and the related induced Roelofs effect, has focused on understanding the consequences of a biased subjective midline on perception and action. However, research that explicitly examines the mechanism responsible for the distortion of subjective midline is lacking. Lathrop, Bridgeman, & Tseng (2011) demonstrated that an offset frame would cause the effect even when it was presented under conditions that would cause the frame to go unperceived due to inattentional

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blindness. It has also been shown that the effect can be obtained using stimuli other than the large rectangular frame that is typically used to demonstrate the phenomenon. Walter & Dassonville (2006) found a robust induced Roelofs effect with a stimulus consisting only of one end of the frame; the effect was present as long as there was an asymmetry between the stimuli in the left and right halves of the visual display. But while these studies have further defined the characteristics of stimuli able to cause the effect, none has explored its underlying mechanism. What is it about an asymmetric visual image that causes a distortion in the observer's subjective midline?

The Roelofs effect is typically tested under visually impoverished conditions. Observers are placed in total darkness and the frame is the primary component of the visual image. The onset of the frame is a very abrupt and salient perceptual event, one that would likely cause immediate attentional capture. One intuitive hypothesis is that the onset of the frame acts to automatically capture attention. The shift of attention toward the frame could, in turn, pull the observer's subjective midline in the same direction. While the findings of Lathrop et al. (2011), indicating that the frame need not be perceived in order to cause the Roelofs effect, might seem to provide evidence against this proposed mechanism for the effect, many other studies have clearly shown that implicit stimuli are capable of affecting the perception of other stimuli, and, more specifically, are capable of influencing the guidance of attention (e.g., Walter & Dassonville, 2005).

Links between shifts of attention and distortions of the egocentric reference frame have not been empirically tested. However, hints in the attention localization literature suggest that these links could exist. Past behavioral research has demonstrated that the accuracy of an attempt to locate a briefly presented target item increases when covert attention is directed toward the target (Butler, 1980; Newby & Rock, 2001; Prinzmetal, Amiri, Allen, & Edwards, 1998; Tsal, 1999; Tsal & Bareket, 1999). Attention directed at a visual target also tends to decrease perceptual biases in the perceived location of the target, such as the foveal bias in perceived location of flashed targets (Bocianski, Müsseler, & Erlhagen, 2010; Fortenbaugh & Robertson, 2011). However, focal attention tends to cause biases in the locations of unattended targets, with the unattended targets seemingly repelled from the attended location (Pratt & Arnott, 2008; Pratt & Turk-Browne, 2002; Suzuki & Cavanagh, 1997). In addition, clinical evidence suggests that the current locus of spatial attention can act as the origin of an egocentric reference frame that is used to encode object locations. McCloskey and Rapp (2000) describe a patient who perceived objects as being in their mirror image locations with respect to the locus of attention (i.e., an object to the right of the attentional locus is mislocalized to the left; see also Flevaris, Montgomery, & Rhodes, 2001; Rhodes & Montgomery, 1999, 2000).

Potential anatomical links between the control of visuospatial attention and the computation of egocentric reference frames can also be drawn from the neuroimaging literature. Vallar et al. (1999) had participants perform a task in which they indicated when a bar, moving laterally on screen, traversed the apparent midline. The researchers observed a significant activation in a network of frontal and parietal regions when participants had to judge the location of the bar relative to midline, compared to a control experiment in which the bar's location was reported within an allocentric reference frame. The strongest activations were observed in the right superior parietal lobule and inferior parietal sulcus—regions that have been implicated in the control of voluntary and reflexive visuospatial attention (Anderson et al., 1994; Corbetta, Miezin, Shulman, & Petersen, 1993; Corbetta, Shulman, Miezin, & Petersen, 1995; Gitelman et al., 1996; Nobre et al., 1997). In another study, Walter and Dassonville (2008) adapted the induced Roelofs effect for use with fMRI, to determine the brain regions that are recruited when individuals make location judgments in the presence of a Roelofs-inducing frame. In separate blocks of trials, participants reported the location of the target in the presence of the offset frame, or performed a control task that involved a color judgment. During the localization task, a significant, primarily right-lateralized activation was observed in the superior parietal lobule, indicating a possible role for this structure in processing the visuospatial contextual information that drives the Roelofs effect.

Recent psychophysical work (Lester & Dassonville, 2011) has also shown that the midline distortion observed in the induced Roelofs effect can be modulated by an observer's attentional goals. Using a modified color-contingency paradigm (see Folk, Leber, & Egeth, 2002, 2008), participants reported the location of a target item (e.g., a red target amid distractors of other colors) presented inside the offset frame. The magnitude of the midline distortion was largest when the frame matched the color of the target item. While this study was designed to examine the effects of attentional filtering and not to explicitly measure discrete shifts of attention, the attentional modulation raises the possibility that shifts of visuospatial attention cause the distortion of an individuals' perception of straight-ahead in the Roelofs effect.

In the current study, we explore the possibility that the distortion of the subjective midline associated with the Roelofs effect is driven by a shift of attention toward the offset frame. Specifically, we examine

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whether shifts of visuospatial attention, using a modified Posner cueing paradigm (Posner, 1980; Posner, Snyder, & Davidson, 1980), affect perceived straight-ahead. On the majority of trials, participants identified a letter that was preceded by a spatial cue that was either spatially nonpredictive (Experiments 1 and 3) or predictive (Experiment 2) of the letter's subsequent location. Accuracy in the identification task allowed for an assessment of the cues' effectiveness in attracting the observer's spatial attention across trials. However, on occasional, unpredictable trials, the letter was replaced with a visual probe whose location was to be reported by the participant. An assessment of the performance in the localization task allowed for a determination of whether the earlier cue and resulting shift of attention are capable of causing a distortion of the participant's spatial reference frame.

Experiment 1

If spatial shifts of attention are the underlying cause of the Roelofs effect, we predict that the participant's subjective midline will be yoked to the locus of spatial attention. Specifically, when attention shifts to the left visual hemifield, the subjective midline will be pulled to the left, causing the participant to report the location of the visual probe as lying further to the right than its actual location; the opposite effect would occur with a rightward attention shift. In contrast, if the subjective midline is not drawn to the locus of attention, localization performance should not be significantly affected by the shift of attention. This pattern of findings would indicate that the asymmetric visual display used to generate the Roelofs effect does so through a mechanism that is independent of any shifts of attention.

Methods

Participants

Fourteen University of Oregon undergraduates with normal or corrected-to-normal vision volunteered to participate for course credit. Participants provided informed consent prior to their participation, with all procedures approved by the Institutional Review Board of the University of Oregon.

Apparatus

Stimuli were back-projected onto a translucent screen (137 × 102 cm), using an Electrohome Marquee 8500 CRT projector (Electrohome, Niagara Fall, ON, Canada) with a screen refresh rate of 60 Hz. Manual responses were collected using a keyboard connected to the host computer. Stimuli were centered at eye-level while participants were seated in a completely darkened room. Participants sat comfortably with their heads steadied by chin and forehead rests, approximately 90 cm from the plane of the presentation screen. Eye position was monitored online using an EyeLink 1000 eye-tracking system (SR Research, Kanata, ON, Canada) in a tower-mounted configuration, operating at a 250-Hz sampling rate. Participants were required to maintain the eyes within a fixation zone throughout the trial, even after the fixation point was extinguished at the start of the trial (the fixation point was removed so that it could not be used as an allocentric localization cue). Trials during which an eye movement or blink occurred were discarded and repeated at the end of the experimental block. A relatively large fixation zone (2.5° radius) was used to allow for the possible small movements of the eyes that occur during fixation in complete darkness, especially with covert attention focused in the periphery (Engbert & Kliegl, 2003; Hafed & Clark, 2002; Laubrock, Engbert, & Kliegl, 2005; but see Horowitz, Fine, Fencsik, Yurgenson, & Wolfe, 2007). However, it is possible that small eye movements within the fixation zone might themselves cause a mislocalization of the visual probes (see, for example, Henriques, Klier, Smith, Lowy, & Crawford, 1998). For this reason, a measure of the average deviation of eye position at target offset was used as a covariate in the statistical analyses of the effects of the attentional cue (see details of the statistical analysis, below).

Probe localization training

Prior to beginning the experiment, each participant completed a short period of training (100 trials) in which they learned an array of five possible locations (8° below fixation, and −3°, −1.5°, 0°, 1.5°, and 3° from midline) for the visual probe that would be used in the later localization trials. Each trial began with the presentation of a central white fixation point (1° in diameter); participants fixated this point and pressed the spacebar when they were ready to begin a trial. After a 213 ms ISI,[1] a small white probe (1° in diameter) appeared in one of the five possible locations for 1 s. Participants were asked to report the perceived location of the probe by pressing one of five corresponding keys on the keyboard with the fingers of the right hand (i.e., thumb on the right arrow key for a probe in the −3° location, index finger on the "1" of the number pad for the probe at the −1.5° location, middle finger on the "2" for the probe at the 0° location, ring finger on the "3" for the probe at the 1.5° location, and little finger on the Enter key of the number pad for the probe at the 3° location).

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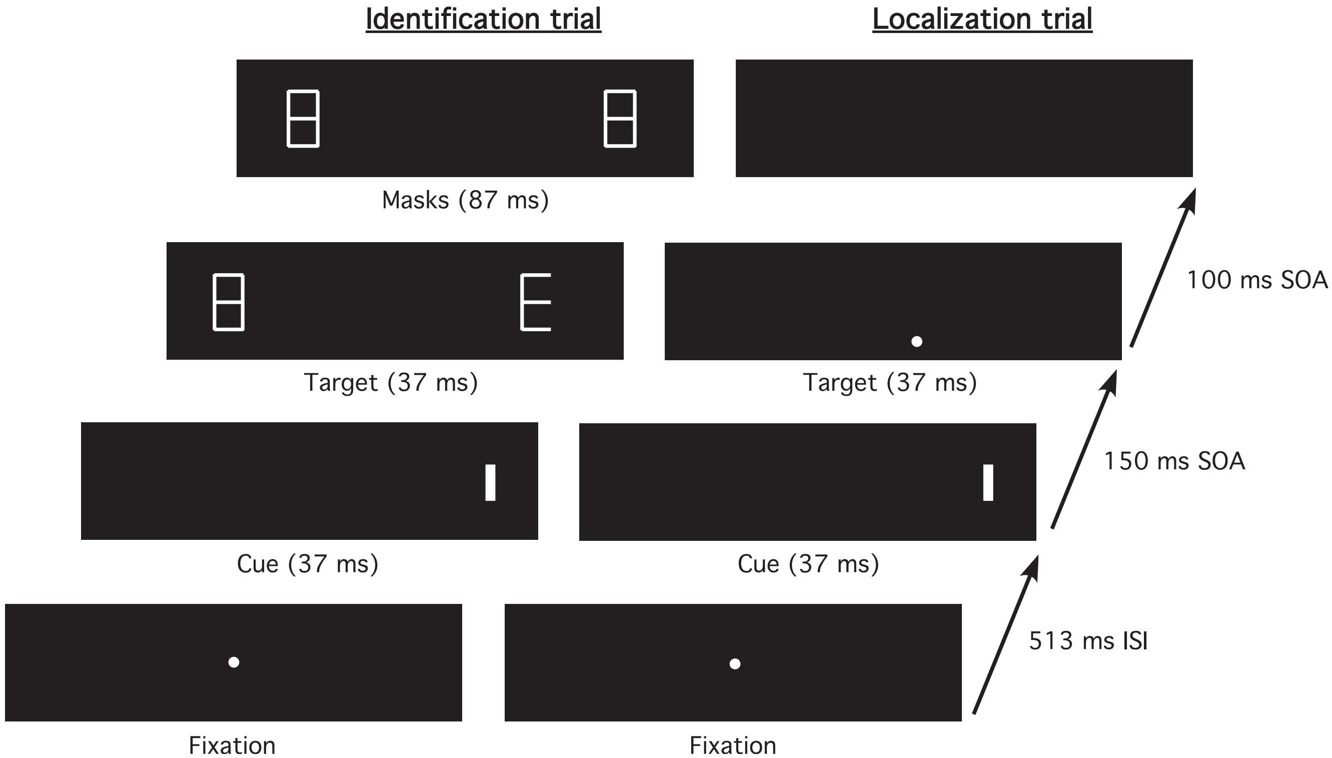

Figure 1. Sample trials of the letter identification (left) and probe localization tasks (right) from Experiment 1. The identification trial is an example of the validly cued condition, in which the cue and target letter appear in the same spatial position. In localization trials, participants reported the perceived location of the visual probe within an array of previously learned probe positions (not seen). All timing procedures were identical across the tasks, except the masks were not presented in the localization trials. The exogenous cue was never predictive of the subsequent target position in either task.

Feedback (1987 ms duration, starting 500 ms after the keyboard response) was included to help participants learn the probe array more quickly and accurately. If participants indicated the correct position of the probe, the word "Correct" appeared just above fixation. If they reported the incorrect location, "Incorrect" appeared along with the actual position of the probe, to assist in learning the probe positions. After the feedback was presented, the fixation point reappeared and participants were free to begin the next trial. Average accuracy for the last ten trials of the training period was 84% ($SE = 3.0$) and significantly above chance ($t(139) = 11.11$, $p < .001$), demonstrating that participants successfully memorized the locations of items in the probe array.

Stimuli and experimental procedure

Each participant completed 21 practice trials to gain familiarity with the task, followed by 252 experimental trials. The majority of the experimental trials (144 of 252 trials) were *letter identification* trials, in which participants reported the identity of a target letter that followed an attentional cue. The remaining trials (108 of 252) were *probe localization* trials, in which participants reported the location of a visual probe in the same manner that was learned in the earlier localization training (previous section). Attention and localization trials appeared in a random order, with no advance warning to indicate the type of trial to expect. Both types of trials included a nonpredictive attention cue that could appear to the left or right of fixation, or bilaterally. Participants were informed of the nonpredictive nature of the cue and were instructed to ignore it and concentrate on either identifying the target letter or reporting the location of the visual probe, whichever appeared in the course of a trial. Participants were instructed to emphasize accuracy in their responses, rather than speed.

Letter identification trials: Every trial (Figure 1, left) began with the presentation of a central fixation point (1° diameter). Participants initiated the trial by moving the eyes to the fixation point, and then pressing the keyboard spacebar with the left hand. The central fixation point then disappeared; after a 513 ms ISI, a small peripheral cue (0.8° in width $\times$ 2.5° in height) appeared for 37 ms. This exogenous cue appeared randomly on the left or right, 19° from fixation, or bilaterally. Following the peripheral cue (150 ms SOA), a single target letter (E or H) and a figure-8 (3° $\times$ 6°)

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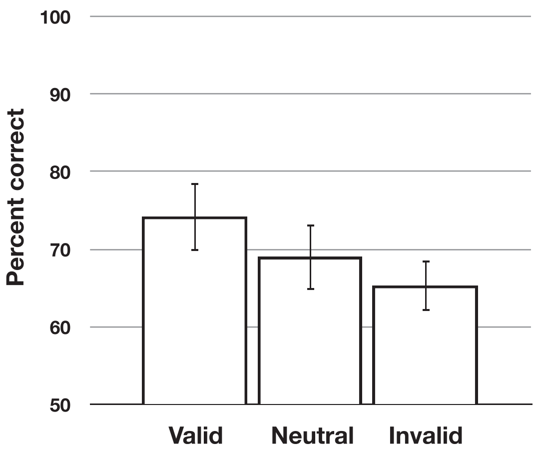

Figure 2. Percent correct in the letter identification task of Experiment 1. Error bars represent standard error estimates for each cue condition.

were presented (37 ms duration) simultaneously, 15° from fixation. After a 63 ms ISI, two visual masks (figure-8, 3° × 6°, 87 ms duration) appeared to obscure any residual visual information.

Participants were instructed to report the identity of the target letter by pressing one of two keys with their left hand ("x" with their index finger if the letter was an H, "z" with their middle finger if the letter was an E). Trials were categorized according to the locations of the exogenous cue and target letter. For valid cue trials, the exogenous cue and target letter appeared on the same side of fixation. In invalid cue trials, the cue and target letter appeared on opposite sides of fixation. Neutral cue trials included bilateral exogenous cues. *Probe localization trials*: Localization trials (Figure 1, right) began in an identical fashion as the identification trials, with a fixation point that was followed after 500 ms by the appearance of an attentional cue presented 19° left or right of the fixation point, or bilaterally. However, no letter targets or visual masks appeared. Instead, following the attentional cue (150 ms SOA), a small white circular probe (1° diameter) appeared in one of the possible probe locations that were learned during the earlier training procedure (see the localization training, above). However, unlike the training period and unbeknownst to the participants, probes in the experimental trials could appear only in the central three locations of the array (8° below fixation, and –1.5°, 0°, or 1.5° from midline), to accommodate possible mislocalizations due to the prior attentional cue, and minimize the occurrence of probes that appeared further right (or left) of the rightmost (or leftmost) locations in the learned array. To end the trial, participants reported the location of the probe using the key press procedure they had learned in the earlier training.

Statistical analyses

The effect of the attentional cue in the letter identification trials was assessed in a repeated-measures ANOVA of identification accuracy, with cue validity (valid, neutral, or invalid) as a factor. In the localization trials, the effects of the attentional cue were assessed in a repeated-measures ANOVA of reported target location, with actual target location (–1.5°, 0°, or 1.5° from midline) and cue location (left, neutral, or right) as factors. In addition, we included as a covariate a measure of the deviation of eye position toward or away from the attentional cue, as a way of controlling for the effects of possible movements of the eyes within the bounds of the fixation window. Deviations of eye position were quantified for each subject by subtracting the average eye position at target offset for trials with rightward cues from those with leftward cues.

Results

A repeated-measures ANOVA of the accuracies in the letter identification trials (Figure 2) demonstrated that there was a significant main effect of cue validity, $F(2, 26) = 7.50$, $p < .005$, with valid cues ($M = 74.3\%$ correct, $SE = 4.46$) resulting in a significantly greater accuracy in letter identification, compared to the neutral ($M = 69.0\%$, $SE = 4.27$) and invalid cues ($M = 65.3\%$, $SE = 3.29$). Separate contrasts revealed that valid cues led to a significantly greater accuracy compared to the neutral, $t(13) = 3.77$, $p < 0.005$ and invalid cues, $t(13) = 2.45$, $p < 0.05$; however, accuracy for neutral cues was not significantly greater than that for invalid cues, $t(13) = -1.65$, $p = 0.124$.

In the localization task (Figure 3), there was a significant main effect of both probe, $F(2, 24) = 57.18$, $p < 0.0001$, and cue position, $F(2, 24) = 39.89$, $p < 0.0001$, but there was no interaction of the two, $F(4, 48) = 1.39$, *ns*, nor did either interact with the eye position covariate (all Fs < 1.86, *ns*). Planned comparisons demonstrated that reported probe location differed significantly between the cued right and left conditions, $t(13) = -6.66$, $p < 0.001$. In the cued right condition, the reported probe location was biased to the left, consistent with a rightward shift in subjective midline. Conversely, there was a bias to the right when the cue appeared left of fixation. Both the cued right and left conditions were significantly different from the neutral cue condition, $t(13) = -6.90$, $p < 0.001$, and $t(13) = 4.66$, $p < 0.001$, respectively. The mean reported difference in the location of the probe (right cue – left cue conditions) was 0.94°, with probes reported in the direction opposite that of the peripheral cue (Figure 3).

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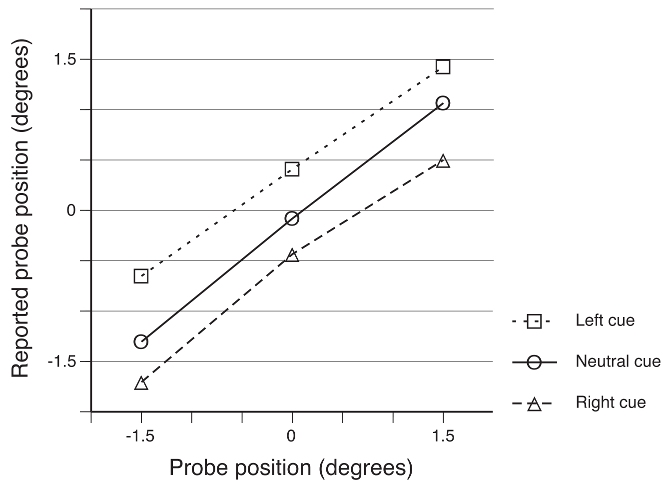

Figure 3. Reported probe location in the localization task of Experiment 1, plotted with respect to the actual probe location (negative values indicate locations to the left of fixation). Data are plotted separately for the left, neutral, and right exogenous cue conditions.

Discussion

In Experiment 1, exogenous attentional cues were used to cause reflexive shifts of attention. Subjects then reported the identity of a subsequent letter (identification trials) or the location of a visual probe (localization trials) in randomly intermixed trials. The pattern of results in the identification trials clearly indicated that the attentional cues were effective at summoning attention, allowing for more accurate identification of the target letter after valid cues.

In the localization trials, a main effect of probe location demonstrated that participants could clearly distinguish the individual probes and compare their locations to those of the array of possible probes learned in the earlier training period. A close examination of Figure 3 indicates that participants tended to report the peripheral probes as being more centrally located than in reality (thus, the slopes of the lines in Figure 3 are less than unity). This effect has been observed in previous experiments (e.g., Bridgeman et al., 1997; Dassonville & Bala, 2004a, 2004b), and is indicative of an expansion of remembered space (and, therefore, an expansion of the spacing between probe locations in the comparison array; Dassonville & Bala, 2004b).

In addition to the influence of actual probe location, the reported probe locations were affected by the presentation of attentional cues, with the probes reported to occupy locations shifted in the direction opposite the exogenous cue. In the traditional induced Roelofs effect, a large frame presented in a location offset from the observer's objective midline has the tendency to cause the subjective midline to become deviated in the direction of the frame (Dassonville et al., 2004; Dassonville & Bala, 2004a). This bias in the subjective midline subsequently causes a pattern of errors in probe localization, with the probe perceived to be shifted in the direction opposite the frame shift. The effects of the lateralized attentional cue in the current experiment strongly mirror (in direction and magnitude) the biased perceptual reports observed in the Roelofs literature, suggesting that the effects are one and the same. This serves as a replication of the findings of Walter and Dassonville (2006), who showed that stimuli much smaller than the typical large frame are able to induce the Roelofs effect.

The results of Experiment 1 also support the hypothesis that shifts of visuospatial attention can bias an observer's subjective midline and possibly serve as the underlying cause of the Roelofs effect. However, there is an alternative explanation that must be entertained. While the paradigm of Experiment 1 did successfully manipulate the distribution of visuospatial attention, it involved the use of displays that were asymmetric in their visual content, with an attentional cue that was presented either to the left or right of the visual display. It may be that the mere presence of an asymmetric display is sufficient to distort participants' subjective midline, independent of any effects that the display may have on attentional deployment. This alternative explanation is examined in Experiment 2, in a paradigm that generates shifts of attention without the use of asymmetric visual displays.

Experiment 2

The deployment of visuospatial attention is influenced by information that falls broadly into two categories: 1) events within the visual environment (i.e., stimulus-driven or exogenous orientation of attention), and 2) the goals/intentions of the observer (i.e., goal-driven or endogenous orientation) (Posner, 1980). In Experiment 1, a classic stimulus-driven manipulation of attention was employed. In Experiment 2, shifts of spatial attention were achieved by providing participants with advance knowledge of the likely position of a target letter. Specifically, a centrally presented endogenous cue indicated the probable location of the target, so that participants could orient spatial attention accordingly. If the perceived location of a visual probe is affected by attentional shifts that are not accompanied by asymmetric visual displays, it would provide strong supporting evidence that the Roelofs effect is driven by a shift of attention toward the illusion-inducing offset frame.

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Methods

Participants

Seventeen University of Oregon undergraduates with normal or corrected-to-normal vision volunteered to participate for course credit. Participants provided informed consent prior to their participation, with all procedures approved by the Institutional Review Board of the University of Oregon.

Apparatus

The apparatus was identical to that in Experiment 1.

Probe localization training

To familiarize themselves with the array of five possible probe locations, participants completed a training procedure identical to that of Experiment 1. Average accuracy for the last ten trials of the training period was significantly greater than chance ($M =$ 79.0% correct, $SE = 3.0$), $t(169) = 9.46$, $p < 0.001$.

Stimuli

All stimuli were identical to Experiment 1, except for the attentional cue. A predictive cue (75% valid) was presented in the center of the display screen after the offset of the fixation point. The endogenous cue consisted of two chevrons (2.5° × 2.5°) that pointed either to the left (i.e., <<) or right (i.e., >>) target position, to indicate the likely position of the subsequent target letter. In neutral trials, the chevrons pointed to both potential target positions (e.g., < >).

Experimental procedure

All procedures were identical to Experiment 1, except where noted. Participants completed 37 practice trials and 296 experimental trials. The majority of the experimental trials were letter identification trials (222 of 296 trials), with the remaining probe localization trials (74 of 296).

Letter identification trials: The majority of the letter identification trials (75%) were valid trials, in which the tips of the chevrons indicated the correct location of the target letter. In invalid trials (12.5%), the incorrect target location was indicated. The remaining trials (12.5%) were neutral trials, in which the chevrons pointed to both locations (e.g., < >), indicating that the target was equally likely to appear at either location. Participants were informed of these probabilities and were encouraged to shift attention in the direction indicated by the cue, because a target letter was likely to appear at that location. An 850 ms SOA elapsed between the onset of the cue and the target letter. Participants responded by indicating the identity of the target letter with a key press, as described in Experiment 1.

Probe localization trials: The localization trials were identical to those of Experiment 1, except for the use of the endogenous attentional cues and the longer SOA (850 ms) described above for the letter identification trials. The endogenous cue was never predictive of the location of the localization probe.

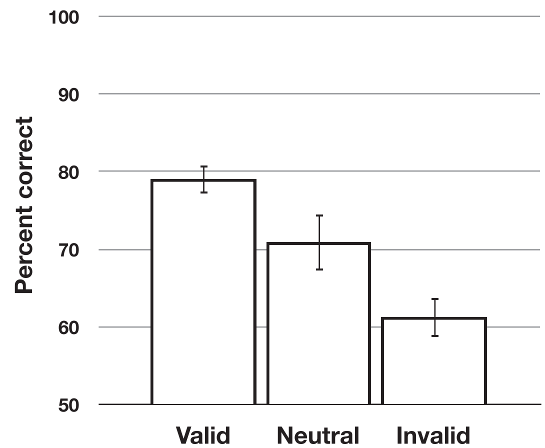

Figure 4. Percent correct in the letter identification task of Experiment 2. Error bars represent standard error estimates for each cue condition.

Statistical analyses

The effect of the endogenous attentional cue in the letter identification trials was assessed in a repeated-measures ANOVA of identification accuracy, with cue validity (valid, neutral, or invalid) as a factor. In the localization trials, the effects of the attentional cue were assessed in a repeated-measures ANOVA of reported target location, with actual target location (−1.5°, 0°, or 1.5° from midline) and cue direction (left, neutral, or right) as factors. As in Experiment 1, possible cue-related deviations of eye position within the fixation window were included as a covariate in the analysis, with these deviations quantified for each subject by subtracting the average eye position at target offset for trials with rightward cues from those with leftward cues.

Results

In the letter identification trials (Figure 4), a main effect of cue validity was again observed, $F(2, 32) =$ 20.20, $p < 0.001$, with participants having a significantly greater accuracy in reporting the target letter when it was proceeded by a valid cue ($M = 79.0\%$ correct, $SE = 1.85$) compared to invalid ($M = 61.23\%$,

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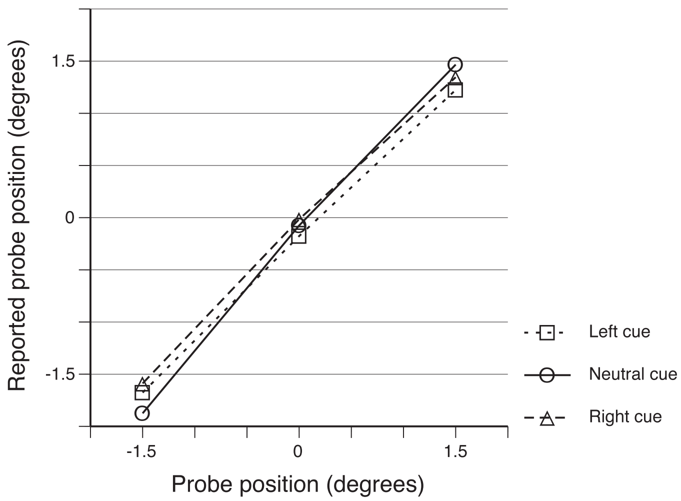

Figure 5. Perceived probe location in the localization task of Experiment 2, plotted with respect to the actual probe location (negative values indicate locations to the left of fixation). Data are plotted separately for the left, neutral, and right endogenous cue conditions.

$SE = 2.54$), $t(16) = 5.84$, $p < 0.001$, and neutral cues ($M = 70.84\%$, $SE = 2.26$), $t(16) = 3.64$, $p < 0.005$. The invalid cue also led to a significant behavioral cost, with a decreased accuracy following invalid cues compared to the trials with neutral cues, $t(16) = -3.17$, $p < 0.005$).

For the localization task (Figure 5), we again observed a significant main effect of probe location, $F(2, 30) = 175.87$, $p < 0.001$. However, the endogenous attentional cue caused no significant effect on the reported location of the probe, $F(2, 30) = 1.38$, *ns*. A significant interaction between cue and probe location, $F(4, 60) = 5.79$, $p = 0.001$, reflected a tendency for probes that were preceded by leftward or rightward attentional cues to be reported as closer to midline than those preceded by neutral cues. Indeed, this interaction became nonsignificant when the neutral cue data were removed from the analysis, $F(2, 30) = 1.22$, *ns*, whereas the pattern of significant effects for probe location, $F(1, 15) = 147.37$, $p < 0.0001$, and nonsignificant effects of cue location, $F(1, 15) = 3.15$, *ns*, remained. In no case did any interaction with the eye position covariate reach significance (all Fs < 1.01, *ns*).

Discussion

In Experiment 2, endogenous central cues were used to elicit shifts of spatial attention. Performance in the letter identification task demonstrated that participants successfully oriented attention to the cued location, with valid cues leading to increased accuracy in identifying the letters, and invalid cues leading to decreased accuracy.

In spite of their success in attracting the participants' attention and influencing performance in the letter identification trials, the endogenous cues of Experiment 2 had no effect on the reported location of the localization probes. This lack of an effect of endogenous shifts of attention, then, provides evidence against the general hypothesis that shifts of attention serve to distort the observer's subjective midline, and against the more specific hypothesis that the Roelofs effect is driven by a reorienting of attention toward the center of the inducing frame. It may be, though, that important differences exist in the way that the subjective midline is affected by exogenous and endogenous shifts of attention, with the subjective midline susceptible to distortions caused by exogenous but not endogenous shifts. Indeed, if the Roelofs-inducing frame causes a reorienting of attention, it is of an exogenous nature. Further, the results of Experiment 1 are consistent with, but do not definitively support, the idea that exogenous shifts of attention lead to a distortion of subjective midline. In Experiment 3, we attempted to eliminate the confounds that existed in Experiment 1 in order to more precisely measure the effects of both an exogenous reorienting of attention and the asymmetric visual display inherent in the Roelofs effect.

Experiment 3

This series of experiments was undertaken to test the hypothesis that the distortion of the observer's midline that underlies the Roelofs effect is caused by a shift of attention to the center of the offset inducing frame. While Experiment 1 demonstrated that a small exogenous attentional cue does indeed induce a Roelofs-like effect, Experiment 2 suggested that it was not attentional shifts per se that cause the effect. However, since Experiment 1 tested the effects of an exogenous cue and Experiment 2 tested the effects of an endogenous one, it could be that the difference in outcomes points to differences in the effects of exogenous versus endogenous shifts of attention, with only exogenous shifts able to cause a bias in the subjective midline. Therefore, we have not yet established whether the Roelofs effect is driven directly by the visual field asymmetry that is inherent in the offset inducing frame, or instead due to the resulting attentional shift that such an asymmetry might evoke. To distinguish between these possibilities, it is necessary to devise a paradigm that successfully dissociates the visual field asymmetry from the resulting shift of attention that might occur.

In Experiment 3, a visual field asymmetry was created by presenting to participants an array of eight

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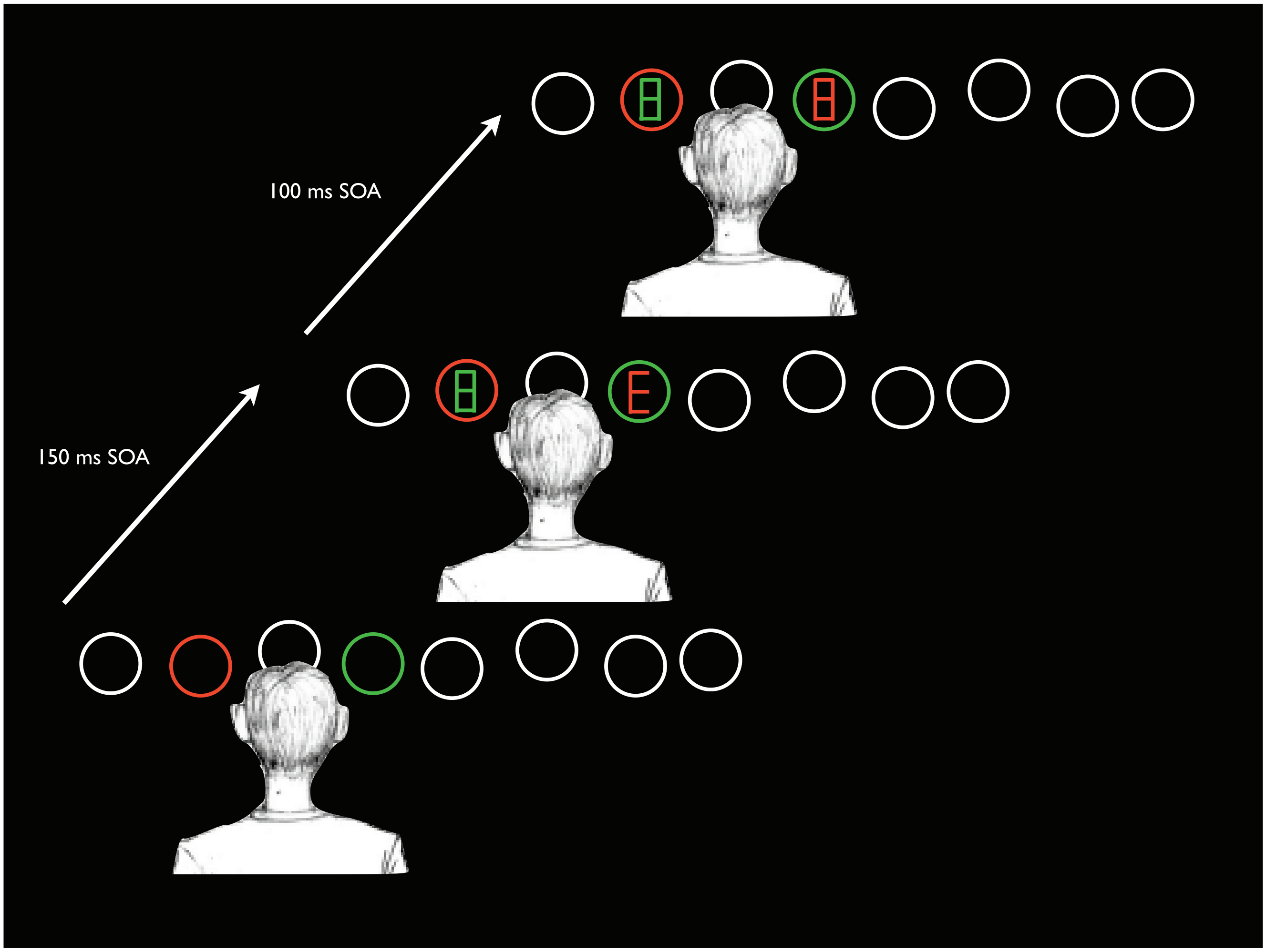

Figure 6. Example of a valid array: invalid cue trial in the letter identification task from Experiment 3, with the participant asked to identify the target letter presented in red. The fixation point (not shown) was presented at eye level, centered on the participant's objective midline. The observer was always positioned halfway between the two possible target letter locations. The array of circles shifted (left or right) around those positions throughout the experiment. In the localization task (not shown), the target and distractor letters and masks did not appear; instead, a small visual probe appeared below the array.

circles that was offset to the left or right of straight ahead (Figure 6). Although this offset array is somewhat different than the typical Roelofs-inducing rectangular frame, it is expected that the resulting asymmetry in the visual field will still be capable of causing a Roelofs effect when participants attempt to determine the location of a visual probe presented below the array. In a letter identification task, participants were instructed to report the identity of a letter that was a specific color (e.g., red). The letter always appeared inside one of two possible circles in the offset array. On some trials, the presentation of the target letter was preceded by a nonpredictive cue that matched the color of the letter (e.g., one red circle in the offset array). Previous work has demonstrated involuntary attentional capture to the location of this type of irrelevant cue, because the color of the cue matches the observer's attentional settings (Folk et al., 2002, 2008; Folk & Remington, 1999, 2006; Folk, Remington, & Johnston, 1992; Theeuwes, 1992, 1994). If the Roelofs effect is driven by shifts of attention, we predict that the perceived location of a visual probe should be modulated by the location of the colored cue. Alternatively, if the Roelofs effect is driven directly by sensory asymmetries in the visual field and is therefore unaffected by shifts of attention, we would predict no effect of the cue; instead, the probe's perceived location should vary with the location of the offset array of circles.

Methods

Participants

Eighteen University of Oregon undergraduates with normal or corrected-to-normal vision volunteered to

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participate for course credit. Participants provided informed consent prior to their participation, with all procedures approved by the Institutional Review Board of the University of Oregon.

Apparatus

The apparatus was identical to that of Experiments 1 and 2.

Localization training

Participants first completed the identical localization training procedure described in the previous experiments, except the probe was positioned 11° below fixation. Average accuracy was significantly greater than chance for the last ten trials of the training session ($M = 80\%$ correct, $SE = 3.0$), $t(179) = 10.03$, $p < 0.0001$.

Experimental procedure

Participants completed 20 practice trials and 252 experimental trials. Participants were instructed that there would be two tasks in the experiment: a letter identification task (comprising 144 of the 252 trials) and a probe localization task (108 trials). Participants never had to perform both tasks in a single trial; they were told the two tasks would be randomized throughout the experiment, with no prior warning to indicate which trial type to expect. In the letter identification task, participants were asked to report the identity of a target letter (an E or H) that would appear simultaneously with a figure-8 distractor, with the letter always of one color (the target color, red or green, was counterbalanced across subjects) and the distractor always of another (the distractor color, green or red). In addition, they were told that the target letter could appear inside either of two colored circles (one red, the other green), and that the colors of the circles were not predictive of the letter position or its identity. For the remaining localization trials, participants were told that the letter would not appear, but would be replaced by a visual probe whose position should be reported just as it had been in the earlier localization training procedure.

Every trial began with the presentation of a central fixation point (white, 1° diameter) in the center of the screen. Participants initiated the trial by moving the eyes to the fixation point, and then pressing the spacebar on a keyboard with the left hand. After 250 ms, an array of eight horizontally arranged circles (each 5.4° in diameter, with a stroke width of 0.3°) was presented 5.5° below fixation (Figure 6). The circles were displaced laterally 8.3° from one another, on average, with an additional jitter factor in the horizontal and vertical dimensions (±0.06 to 1.1°, randomly selected each trial) so as to preclude their use as stable allocentric cues across trials. The entire array subtended approximately 63°, with the center of the array offset 14° to the left or right of objective midline, such that the majority of the circles fell in one visual hemifield on any given trial. On a minority of trials (96 of 252 trials), all circles in the array were white; in the remaining trials (156 trials), circles in the array were white, with the exception of one that was of the target color and one that was of the distractor color. When they appeared, the two colored circles were always in the array positions immediately flanking the participant's objective midline, and were not jittered in their positions (however, the constant change in the locations of the other circles, and in the entire array, gave the strong subjective impression that these colored circles were also jittered). It was expected that the circle having the target color would act as an exogenous cue that would attract the participant's attention, since its color matched that of the target letter for which the participant was searching.

Letter identification trials: After the onset of the circle array (150 ms SOA), a target letter (E or H, 2.7° by 4.2°, of the target color) appeared inside one of the circles that flanked the participant's objective midline. A single nontarget figure-8 distractor (2.7° by 4.2°, in the distractor color) was presented in the corresponding circle in the other hemifield. After 71 ms, both the target letter and distractor were extinguished, followed after a 29 ms ISI by the presentation of two figure-8 masks (4 ms duration). Subsequently, all stimuli were extinguished, and participants ended the trial by pressing one of two keys with the left hand to indicate the identity of the target letter ("x" with the index finger if the letter was an H, "z" with the middle finger if the letter was an E). After a 500 ms intertrial interval, the fixation point reappeared and participants were free to begin the next trial.

For the identification trials, trials were categorized according to whether the circle array and cue circle locations were consistent with the location of the target letter. Trials in which the target letter appeared inside the circle with the matching color (i.e., both were of the target color) were categorized as valid cue trials. Invalid cue trials were those in which the target letter appeared in the circle with the distractor color. Neutral cue trials contained no colored circles; that is, all the circles were a uniform white. Similarly, trials in which the circle array was offset to the same side as the target letter (e.g., both were to the right of fixation) were categorized as valid array trials. Trials in which the circle array was offset in the direction opposite the target letter were considered invalid array trials.

Probe localization trials: Localization trials began in the same manner as the identification trials, and were

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identical through the presentation of the circle array. However, after a 150 ms SOA from array onset, a localization probe (0.5° diameter, 71 ms duration, with the same color as the target letter in the identification trials) was presented instead of a target letter. The probe appeared 11° below fixation, randomly in one of the central three possible probe positions learned earlier in the localization training (–1.5°, 0°, or 1.5° from participant's midline). After the probe was extinguished, participants pressed one of five buttons with the right hand to indicate the perceived position of the probe. After a 500 ms intertrial interval, the fixation point reappeared and participants were free to begin the next trial.

In the localization trials, trials were categorized according the locations of the circle array (right array or left array) and the location of the circle with the target color (right cue, left cue, or neutral cue).

Statistical analyses

The effects of the array location and color-contingent attentional cue in the letter identification trials was assessed in a repeated-measures ANOVA of identification accuracy, with array location (valid or invalid) and cue validity (valid, neutral, or invalid) as factors. In the localization trials, the effects of the array location and attentional cue were assessed in a repeated-measures ANOVA of reported probe location, with actual probe location (–1.5°, 0°, or 1.5° from midline), array location (left or right) and cue location (left, neutral or right) as factors.

Results

In an assessment of letter identification accuracy (Figure 7), a repeated-measures ANOVA with factors of cue and array validity revealed a significant main effect, $F(2, 34) = 5.95$, $p = 0.006$, of cue validity. In contrast, there was no significant effect of array validity, $F(1, 17) = 0.04$, *ns*, and the interaction between cue and array validity also did not reach significance, $F(2, 34) = 1.58$, *ns*. Because the factor of array validity had no significant effect on identification accuracy, we collapsed across this factor in subsequent analyses. Accuracy in the valid cue condition ($M = 81.3\%$, $SE = 3.0$) was significantly greater than in the invalid cue condition ($M = 74.2\%$, $SE = 2.7$), $t(17) = 3.30$, $p = 0.004$, and marginally greater than in the neutral cue condition ($M = 76.9\%$, $SE = 2.8$) $t(17) = 2.09$, $p = 0.052$). The identification accuracies between the invalid and neutral cue conditions did not significantly differ, $t(17) = -1.39$, *ns*.

In the localization task, the main effects of probe location, $F(2, 34) = 80.18$, $p < 0.0001$, and array

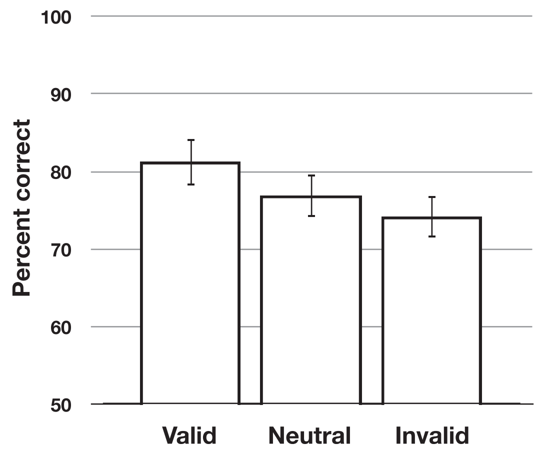

Figure 7. Percent correct in the letter identification task of Experiment 3. Error bars represent standard error estimates for each cue condition.

position, $F(1, 17) = 20.55$, $p < 0.0001$, reached statistical significance, and there was a small but significant interaction between these two factors, $F(2, 32) = 4.25$, $p = 0.02$) (Figure 8). Importantly, and in contrast to the results of Experiment 1, there was no significant main effect of the attentional cue, $F(2, 34) = .87$, *ns*, nor did this factor interact with any other factor (all Fs $< .79$).

Discussion

In the letter identification task of Experiment 3, accuracy was significantly affected by the location of the target-colored cue that preceded the presentation of the target letter. When this cue validly indicated the subsequent target letter location, accuracy increased. This finding demonstrated that the manipulation of attentional set effectively allowed the colored cues to capture attention, with the locus of attention being drawn to the cue that shared the target's color. Importantly, accuracy in the letter identification task was unaffected by the location of the circle array, indicating that the color-contingent manipulation of attention was effective at overriding any attentional attraction that the offset array might have otherwise had.

While letter identification accuracy was affected by the location of the color-contingent attentional cue and not the location of the circle array, there was an opposite pattern of effects in the probe localization task. Specifically, the perceived location of the probe was modulated by the location of the offset circle array, but not by the location of the attentional cue. The bias in localization caused by the offset array mirrored the typical Roelofs effect, with the probe's location reported to be shifted in the direction opposite the array offset. It could be argued that the array of circles

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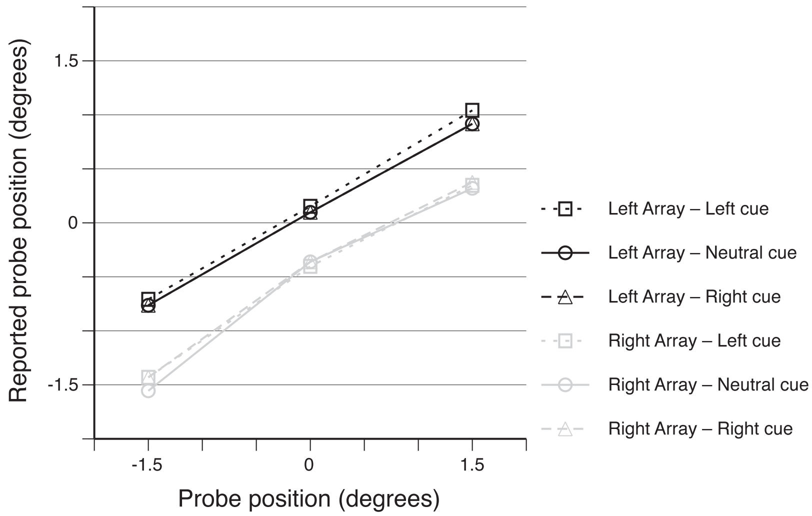

Figure 8. Perceived probe location in the localization task of Experiment 3, plotted with respect to the actual probe location (negative values indicate locations to the left of fixation). Data are plotted separately for the different combinations of cue and array locations.

might serve as an allocentric cue in which to encode the location of the probe, which might override the egocentric distortion that would otherwise cause the Roelofs effect. However, we took the step of jittering the spatial locations of the circles within the array so as to minimize this possibility. Although we cannot guarantee that our attempts to minimize the effects of allocentric coding were completely successful, the significant main effect of array position demonstrates that this atypical inducing stimulus is still capable of generating a Roelofs effect.

In contrast to the mislocalizations caused by the offset array of circles, localization was unaffected by the color-contingent shift of attention. Our original hypothesis suggested that the observer's subjective midline was yoked to the locus of attention, and that the Roelofs effect was driven by the attention-attracting characteristics of the offset inducing frame. However, the findings of Experiment 3 indicate that it is possible to evoke a Roelofs effect through the presentation of an asymmetric visual display *even when attention is attracted in a direction opposite the asymmetry*. This clear dissociation of the Roelofs effect and the locus of attention disproves our hypothesis definitively.

General discussion

In three experiments we examined the effect of orienting visuospatial attention on observers' perception of spatial location. Experiment 1 demonstrated that nonpredictive exogenous cues are capable of causing a Roelofs-like effect, indicating that the Roelofs effect is not dependent on the use of the typical large inducing frame. However, the results of Experiment 1 did not conclusively demonstrate that it was a shift of attention that caused the distortion, since the asymmetry inherent in a visual display containing an exogenous attentional cue might have been sufficient to drive the distortion independent of any shift in the locus of spatial attention. Experiment 2 used a central endogenous cue that prompted a shift of attention without the use of an asymmetric visual display. The resulting shift of attention was found to be incapable of inducing a distortion of the perceived location of a visual probe. Finally, the paradigm of Experiment 3 used a color-contingent attentional manipulation to successfully dissociate a shift of attention from the direction of an asymmetry in the visual display. The results provide clear evidence that it is the asymmetry of the visual display and not any accompanying shift of attention that drives the Roelofs effect.

The finding that the Roelofs effect cannot be attributed to a shift of attention toward the offset frame may seem at odds with previous results from this lab, where it was demonstrated that the magnitude of the Roelofs effect can be modulated by an observer's attentional set (Lester & Dassonville, 2011). However, a closer examination reveals that these findings are not inconsistent. The results of Lester and Dassonville (2011) simply demonstrated that attentional control settings can modulate the salience of contextual information that provide cues for establishing the observer's spatial reference frame, without addressing the mechanism by which these cues have their effect. While an increased salience of the Roelofs-inducing frame might cause it to serve as a more reliable attractant of the locus of attention, the current results

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indicate that the Roelofs effect itself is not directly caused by any resulting shift of attention. Instead, it would seem that the increased salience of the frame brought about by attentional set may increase the magnitude of the Roelofs effect by amplifying the effects of the asymmetry of the visual field inherent in the Roelofs-inducing frame.

Although the results presented here indicate that the Roelofs effect is caused by an asymmetry between the left and right visual fields independent of any shifts of attention, it remains to be determined how the asymmetry causes the underlying distortion of the observer's subjective midline. One possibility is that the visual system uses the middle of the full extent of the visual field as a cue to form a representation of the direction that the head is facing, for use as the origin for an egocentric reference frame. This visual cue would not be used exclusively, since it is clear that vestibular and proprioceptive cues would also contribute (as evidenced by the fact that observers are still capable of making egocentric judgments about an object's location even when that object is perceived in otherwise complete darkness). Under normal viewing conditions, the visual field is reliably symmetrical around the observer's objective midline, and would serve as a useful cue to form a veridical representation of straight-ahead. However, this cue would prove to be less reliable when the observer is in an impoverished visual environment where asymmetries in the visual field would become more prominent, resulting in the Roelofs effect. Under these circumstances, even a small offset stimulus is capable of creating an asymmetry that would lead to the illusion.

Keywords: Roelofs effect, illusion, subjective midline, attention, reference frames

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Footnote

[1]All stimulus durations, ISIs and SOAs are reported according to the methods of Bridgeman (1998), taking into account the 60 Hz refresh rate and 4 ms decay of the CRT projector.

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