Temporal course of position shift for a peripheral target

Yuki Yamada Department of Behavioral and Health Sciences, Kyushu University, Fukuoka, Japan

Kayo Miura Department of Behavioral and Health Sciences, Kyushu University, Fukuoka, Japan

Takahiro Kawabe Department of Behavioral and Health Sciences, Kyushu University, Fukuoka, Japan

When a target is presented near a leading cue stimulus, the perceived location of the target is displaced from the cue (attentional repulsion). On the other hand, a memorized target is sometimes mislocalized toward the cue (attentional attraction). The present study aimed at clarifying the temporal relationship between attentional repulsion and attentional attraction. We used a relative judgment task wherein observers judged whether the horizontal location of the target circle was displaced leftward or rightward from the location of a vertically separated probe disk. In Experiments 1 and 2, the stimulus-onset asynchrony (SOA) between the target and the probe was manipulated from 0 ms to 2000 ms. Repulsive and attractive position shifts were observed at short and long target–probe SOAs, respectively. In Experiment 3, we found that both the cue–target SOA and the target–probe SOA governed the repulsion and attraction in different ways. The results suggest that attentional repulsion and attentional attraction occur at different visual processing stages.

Keywords: attention, localization, spatial memory, spatial cueing

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Introduction

Visual localization is often less than perfect. This is because the localization mechanism is vulnerable to several factors. For example, the localization of a stationary object is influenced by the object's retinal eccentricity (Adam, Paas, Ekering, & van Loon, 1995; Müsseler, van der Heijden, Mahmud, Deubel, & Ertsey, 1999), exposure duration (Adam, Ketelaars, Kingma, & Hoek, 1993; Adam et al., 1995), retention interval (Müsseler et al., 1999; Sheth & Shimojo, 2001, 2004; Werner & Diedrichsen, 2002), eye movements (Honda, 1989; Matin & Pearce, 1965; Ross, Morrone, & Burr, 1997), motion direction at a distant location (Watanabe, 2005; Whitney, 2006; Whitney & Cavanagh, 2000), prior adaptation to unidirectional motion (Nishida & Johnston, 1999; Snowden, 1998), and prior adaptation to contrast polarity (McGraw, Levi, & Whitaker, 1999; Whitaker, McGraw, & Levi, 1997).

In addition to these factors, it is known that attention plays a critical role in localizing a visual object. Previous studies using a spatial cueing paradigm have shown that localization precision is affected by a preceding cue, that is, the precision of localization is higher at a cued location than at uncued locations (Tsal & Bareket, 1999). A similar role of attention in increasing localization precision has also been discerned in studies that employed a dual-task paradigm (Prinzmetal, Amiri, Allen, & Edwards, 1998; Tsal & Bareket, 2005) or inattentional blindness (Newby & Rock, 2001). The results of these previous studies have converged on the conclusion that attention guarantees a finer level of localization.

Attention is also related to the accuracy of localization, in the form of biases. For example, shortly after the presentation of a peripheral cue stimulus (about 100 ms), the perceived location of a target shifts away from a cued location (attentional repulsion; Suzuki & Cavanagh, 1997). In Suzuki and Cavanagh's study, the observers were asked to judge the horizontal misalignment of vertically aligned verniers. When peripheral cues that involuntarily captured spatial attention were presented before the vernier presentation (e.g., Carrasco & McElree, 2001; Eriksen & Collins, 1969; Nakayama & Mackeben, 1989; Posner, 1980), each vernier location perceptually shifted as if repelled from each cue, resulting in a horizontal offset of the verniers. The researchers suggested that attentional repulsion is due to an inhibitory process around the fringe of the cued location induced by transient attention and not due to a by-product of apparent motion or any figural aftereffect. Moreover, attentional repulsion was also triggered by a lateralized auditory cue (Arnott & Goodale, 2006) and by a color singleton (Pratt & Arnott, 2008). Because a lateralized auditory cue (e.g., Spence & Driver, 1997) and a color singleton (e.g., Theeuwes & Burger, 1998) capture spatial attention, those findings seem to support the attentional origin of attentional repulsion.

On the other hand, it has also been reported that a target is often mislocalized in the direction of a cued location

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(Uddin, Kawabe, & Nakamizo, 2005; Yamada, Kawabe, & Miura, 2008). Yamada et al. tested whether mislocalization toward a flashed illusory contour occurred due to attentional allocation to the location. They presented inward- and outward-notched disks in the left and right peripheral visual fields, keeping physical stimulation at the cued locations equal. The inward-notched disks perceptually formed Kanizsa's subjective contours, inevitably attracting the observers' attention (Senkowski, Röttger, Grimm, Foxe, & Herrmann, 2005). The researchers supposed that the subjective contours would serve as preceding peripheral cues even without there being any significant difference in physical components between the inward- and outward-notched disks. Because the outward-notched disks do not generate a subjective contour, they do not attract visual attention, whereas the inward-notched disks do. The inward- and outward-notched disks were presented simultaneously in the left and right visual fields, and the target emerged around the midpoint between the inducers. When the observers were asked to manually indicate the target location via a mouse cursor, the reproduced location was shifted toward the inward-notched disks that perceptually generated subjective contours and attracted attention. From these results, Yamada et al. concluded that the mislocalization toward subjective contours was a result of a cue-induced attentional shift. Their suggestion is consistent with a previous study showing that the reduction of foveal bias stemmed from attention shift toward peripheral post cues (Uddin et al., 2005). In this study, we refer to this position shift toward a peripheral cue as "attentional attraction."

Although attentional repulsion and attentional attraction are related to spatial attentional distribution, their relationship is still unclear. In this study, we focused on the role of temporal factors on these attention-induced position shifts. As noted earlier, previous studies on attentional repulsion have usually measured target locations with a relative judgment of vernier locations (e.g., Arnott & Goodale, 2006; Pratt & Arnott, 2008; Suzuki & Cavanagh, 1997) in which a target location was compared with another target location simultaneously. In contrast, previous studies on attentional attraction have used mouse pointing (Uddin et al., 2005; Yamada et al., 2008). Attentional repulsion has been reported in a task involving simultaneous localization of a target by a probe, while attentional attraction has been reported in a task involving delayed localization of a target by a probe (i.e., a mouse cursor). In fact, it has been shown that the mouse pointing that several previous studies have employed usually takes approximately 1 s to complete the localization (Pratt & Turk-Browne, 2003). However, no direct evidence has been put forward for the temporal relationship between attentional repulsion and attentional attraction. Thus, there has been no research investigating the temporal course of mislocalization for peripheral objects by systematically controlling temporal intervals between a cue and a target and/or between a target and a probe.

In the present study, we tested the temporal relationship between attentional repulsion and attentional attraction. To replicate these phenomena in the same localization procedure, we used a relative judgment task, in which observers made a spatial judgment on the horizontal misalignment of target and probe stimuli as in the vernier discrimination task. Moreover, we manipulated the stimulus-onset asynchrony (SOA) between the target and probe stimuli from 0 ms to 1250 ms (Experiment 1). In this experiment, we predicted that attentional repulsion would occur at the target–probe SOA of 0 ms while attentional attraction would occur at the target–probe SOA of 1250 ms. Experiment 2 tested these effects with a finer time course (8 steps from 0 to 2000 ms). In Experiment 3, we examined the effects of the cue–target SOA as well as the target–probe SOA on the magnitudes of repulsion and attraction effects by varying both the SOAs simultaneously.

Experiment 1

Methods

Observers

Five observers (KI, QK, HO, AY, and KY) and one of the authors (YY) participated in Experiment 1. All had normal or corrected-to-normal visual acuity, and all except for YY were naive as to the purpose of the present study.

Apparatus and stimuli

Stimuli were displayed on a CRT monitor with a 1024 × 768 pixel resolution and a 75-Hz vertical refresh rate. A PC/AT compatible computer was used to control the presentation of the stimuli and collection of data. Figure 1a provides a schematic representation of the time course of the stimuli used in Experiment 1. The stimuli consisted of a fixation cross, a cue, a target, and a probe. The stimuli were displayed on a gray background (43.5 cd/m^2). The color of the fixation cross and the cue was white (91.0 cd/m^2). The color of the target and the probe was black (1.2 cd/m^2). The viewing distance was 60 cm. The fixation cross was always presented at the center of the screen. The cue was a rectangle of 4° × 1°. The target and probe were each a small circle subtending a visual angle of 0.4°. The horizontal distances between the cue and the center of the display and between the target and the center of the display were 12° and 8° (on average), respectively. In each trial, the cue and target were presented in the same visual hemifield (right or left), and the hemifield randomly varied across trials. The centers of the cue and the target were 6.13° above the center of the screen, and the probe was positioned 6.13° below the center of the screen.[1] The duration of the cue, the target, and the probe was 50 ms. In Experiment 1, the SOA

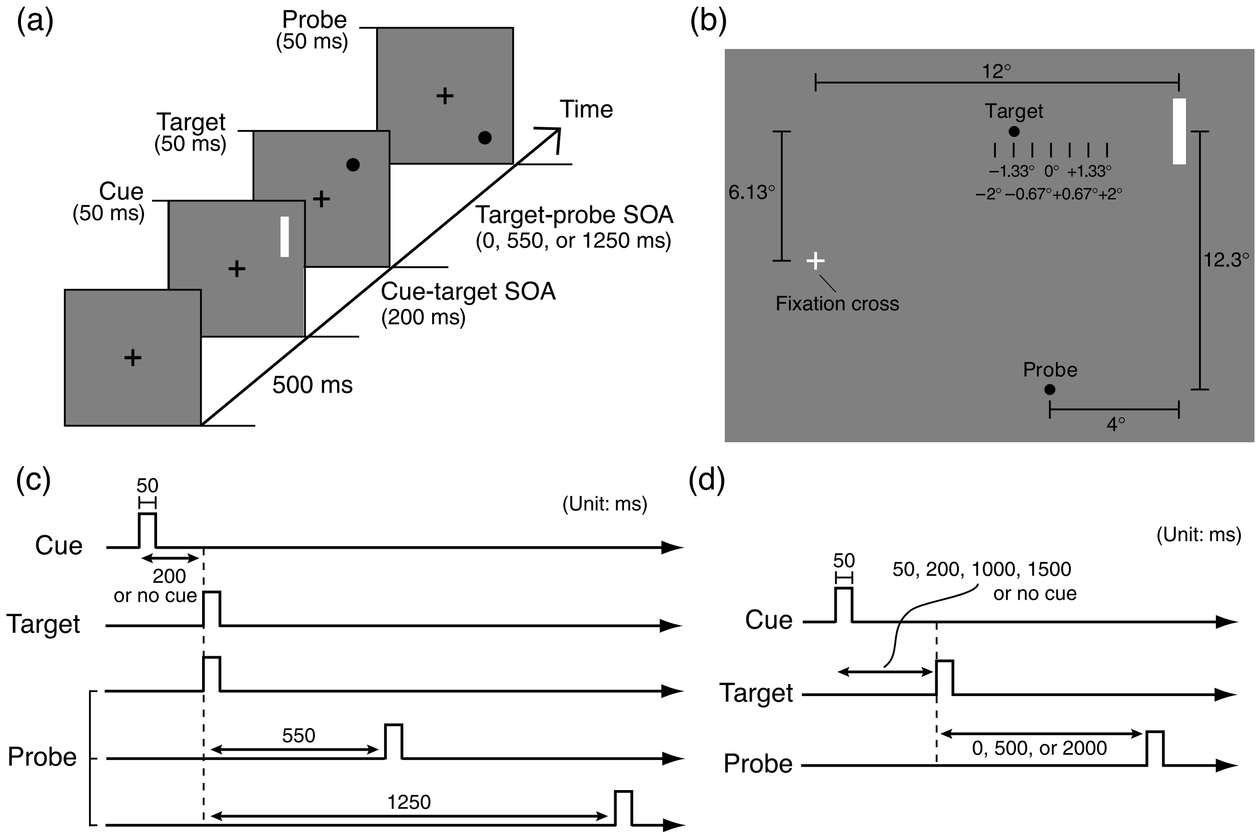

Figure 1. (a) Schematic representation of the time course of a trial in Experiment 1 (not scaled; see main text). (b) Stimulus presentation when stimuli were presented in the right visual field in the 0-ms condition of Experiment 1 (not scaled). When stimuli were presented in the left visual field, the horizontal positional relationship among stimuli was reversed. In both visual fields, the target position with minus values indicates horizontal positions near the center of the screen. (c) The timeline of a trial in Experiment 1. (d) The timeline of a trial in Experiment 3.

between the target and the probe was set at 0, 550, or 1250 ms (i.e., in the 0-ms condition, the target and probe appeared and disappeared simultaneously). In each trial, the horizontal position of the target was varied in 7 or 13 steps[2] of 0.67° (0-ms condition: −2.00, −1.33, −0.67, 0.00, +0.67, +1.33, and +2.00°; 550- and 1250-ms condition: −4.00, −3.33, −2.67, −2.00, −1.33, −0.67, 0.00, +0.67, +1.33, +2.00, +2.67, +3.33, and +4.00°, the minus values denote positions near the center of the screen). The horizontal position of the probe was always the same as that of the target in the 0.00° condition (Figure 1b).

Procedure

The experiment was conducted in a darkened room. The observer's view was fixed by using a chin and head rest. The observers initiated each trial by pressing the spacebar of a computer keyboard. The cue was presented for 50 ms after a blank of 500 ms. Then, after an interstimulus interval (ISI) of 150 ms, the target appeared and lasted for 50 ms. Thereafter, the probe was presented for 50 ms with one of three target–probe SOAs. As a control, a condition without the cue was also tested (the no-cue condition). The observers were instructed to gaze at the fixation cross throughout the experiment and to judge whether the target appeared on the left or right of the probe. The timeline of a trial in Experiment 1 is illustrated in Figure 1c. In Experiment 1, the method of constant stimuli was used. Trials were blocked with respect to each of the three target–probe SOAs (0, 550, and 1250 ms) and two cue conditions (cue and no cue), and consequently, there were six blocks in total. A block consisted of seven or 13 horizontal positions, two visual fields (right and left), and 10 repetitions; they occurred in a pseudo-randomized fashion. The observers performed 1320 trials in total, and it took approximately 1 h to complete Experiment 1 for each observer.

Results

Using the psignifit program implemented in MATLAB (Wichmann & Hill, 2001a, 2001b), we calculated the point of subjective equality (PSE) by fitting a logistic function (Finney, 1971) to the observational data, which were the proportion of the trials wherein each observer reported the target to be horizontally closer to the cued location than

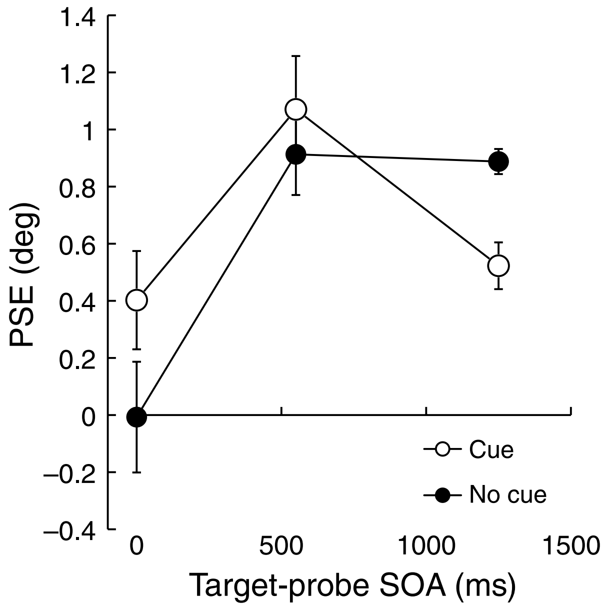

Figure 2. Mean estimated PSE across observers for each condition in Experiment 1. Positive and negative values denote foveal and peripheral mislocalizations, respectively. Error bars indicate within-subject standard errors of the mean (Cousineau, 2005).

the probe. We assessed the goodness of fit by calculating the deviance and cumulative probability estimate, and we confirmed that the logistic function was well fitted ($p < 0.95$).[3]

The results of Experiment 1 are shown in Figure 2. A positive PSE value means mislocalization toward the fovea. A two-way within-subject analysis of variance (ANOVA) with cue (cue and no cue) and target–probe SOA (0, 550, and 1250 ms) as factors was performed on the PSE. The ANOVA revealed a significant main effect of target–probe SOA ($F(2, 10) = 6.33$, MSE = 0.307, $p < 0.02$). However, a main effect of cue was not significant ($F(1, 5) = 0.64$, MSE = 0.064, $p > 0.46$). There was a significant interaction ($F(2, 10) = 8.56$, MSE = 0.055, $p < 0.007$). Simple main effects analyses of the interaction indicated that, in the 0-ms condition, the target in the cue condition was significantly displaced more foveally than that in the no-cue condition ($F(1, 15) = 8.72$, MSE = 0.058, $p < 0.001$). Moreover, in the 1250-ms condition, the target in the cue condition was significantly displaced more peripherally than that in the no-cue condition ($F(1, 15) = 6.92$, MSE = 0.058, $p < 0.02$). However, in the 550-ms condition, there was no difference between the cue and no-cue conditions ($F(1, 15) = 1.29$, MSE = 0.058, $p > 0.27$). In the cue and no-cue conditions, the simple main effects of target–probe SOA were significant (cue: $F(2, 20) = 4.21$, MSE = 0.761, $p < 0.03$; no cue: $F(2, 20) = 9.13$, MSE = 1.649, $p < 0.002$). Multiple comparisons by Ryan's (1960) method[4] indicated that in the cue condition the target with 550-ms target–probe SOA was significantly displaced more foveally than with a 0-ms target–probe SOA ($t(20) = 2.72$, MSE = 0.181, $p < 0.02$). Moreover, in the no-cue condition, the target with 550- and 1250-ms target–probe SOAs was significantly displaced more foveally than with a 0-ms target–probe SOA (550 ms: $t(20) = 3.75$, MSE = 0.181, $p < 0.002$; 1250 ms: $t(20) = 3.65$, MSE = 0.181, $p < 0.002$). A one-sample t-test revealed that the target was significantly displaced more foveally from zero (i.e., the actual position) in 0 ms of the cue condition and in 550 and 1250 ms of the no-cue condition (ps < 0.05).

Discussion

The results of Experiment 1 showed that a significant foveal bias occurred in the 550- and 1250-ms conditions but not in the 0-ms condition when the cue stimuli were not presented. This increment of foveal bias corresponding to the increase of target–probe SOA was also shown in previous studies (Müsseler et al., 1999; Sheth & Shimojo, 2001).

More importantly, attentional repulsion and attentional attraction were clearly observed. At the target–probe SOA of 0 ms, that is, when the target and the probe were presented simultaneously, the target was significantly displaced repulsively from the cued position. This was because attentional repulsion occurred from the cued position (Suzuki & Cavanagh, 1997). On the other hand, there was no difference between the cue and no-cue conditions at the target–probe SOA of 550 ms. The results suggest that foveal bias and attentional attraction cancelled each other out. At the target–probe SOA of 1250 ms, attentional attraction was shown. Thus, attentional attraction occurred after the peak of foveal bias and lasted at least until the target–probe SOA of 1250 ms. Therefore, the results suggest that Experiment 1 successfully replicated attentional repulsion and attentional attraction with the same localization procedure.

Experiment 2

Experiment 1 revealed the temporal course of localization bias, wherein attentional repulsion turned into attentional attraction with an increase of the target–probe SOA. However, the coarse configuration of the target–probe SOA could specify neither when attentional repulsion vanished nor how long attentional attraction lasted. To resolve this issue, we again closely tested the effect of the target–probe SOA on attentional repulsion and attentional attraction with eight target–probe SOAs. In Experiment 2, we employed 0-, 100-, 200-, 400-, 600-, 1000-, 1600-, and 2000-ms SOAs, while in Experiment 1 we employed 0-, 550-, and 1250-ms SOAs. Here, the 100-, 200-, and 400-ms conditions were set up to test when attentional repulsion vanished. The 1600- and 2000-ms conditions were set up to test how long attentional attraction lasted.

Methods

Observers

Two naive observers (DK and KY) and one of the authors (YY) participated in Experiment 2. All had normal or corrected-to-normal visual acuity.

Apparatus, stimuli, and procedure

The apparatus, stimuli, and procedure used in Experiment 2 were identical to those used in Experiment 1 except for the following: The horizontal position of the target was varied with the randomly interleaved double staircase method (one-up/one-down, step size was 0.3°). One staircase started at the most foveal target location (i.e., −2.67°), whereas the other interleaved staircase started at the most peripheral target location (i.e., +2.67°). Each staircase ended after 20 reversals of the staircase. No explicit feedback for the correctness of responses was provided. Eight target–probe SOA conditions were employed (0, 100, 200, 400, 600, 1000, 1600, and 2000 ms) with cue and no-cue conditions. The target–probe SOA and cue conditions were blocked, and the order of the blocks was randomized across observers. It took approximately 3 h to complete this experiment for each observer.

Results

We individually estimated the PSE by fitting a logistic function to the proportions of trials wherein the observers reported the target to be horizontally closer to the cued location than the probe as a function of target locations. The proportions for each target location were calculated based on the data of at least four staircase measurements for each condition (Figure 3a). Moreover, we calculated localization bias by subtracting the PSE value in the cue condition from the PSE value in the no-cue condition. Positive and negative values denote attraction toward the cue and repulsion from the cue, respectively. The results showed that repulsion from the cue was observed at the target–probe SOA from 0 to 200 ms. Afterward, localization bias reversed to attraction toward the cue at around the target–probe SOA of 500 ms, and the reversal lasted until the target–probe SOA of 2000 ms.

A two-way ANOVA with cue and target–probe SOA as factors was performed on the mean PSE. The ANOVA revealed a significant main effect of target–probe SOA ($F(7, 14) = 3.41$, MSE = 0.138, $p < 0.03$). However, there was no significant main effect of cue ($F(1, 2) = 0.01$, MSE = 0.478, $p > 0.94$). There was a significant interaction ($F(7, 14) = 13.12$, MSE = 0.021, $p < 0.0001$).

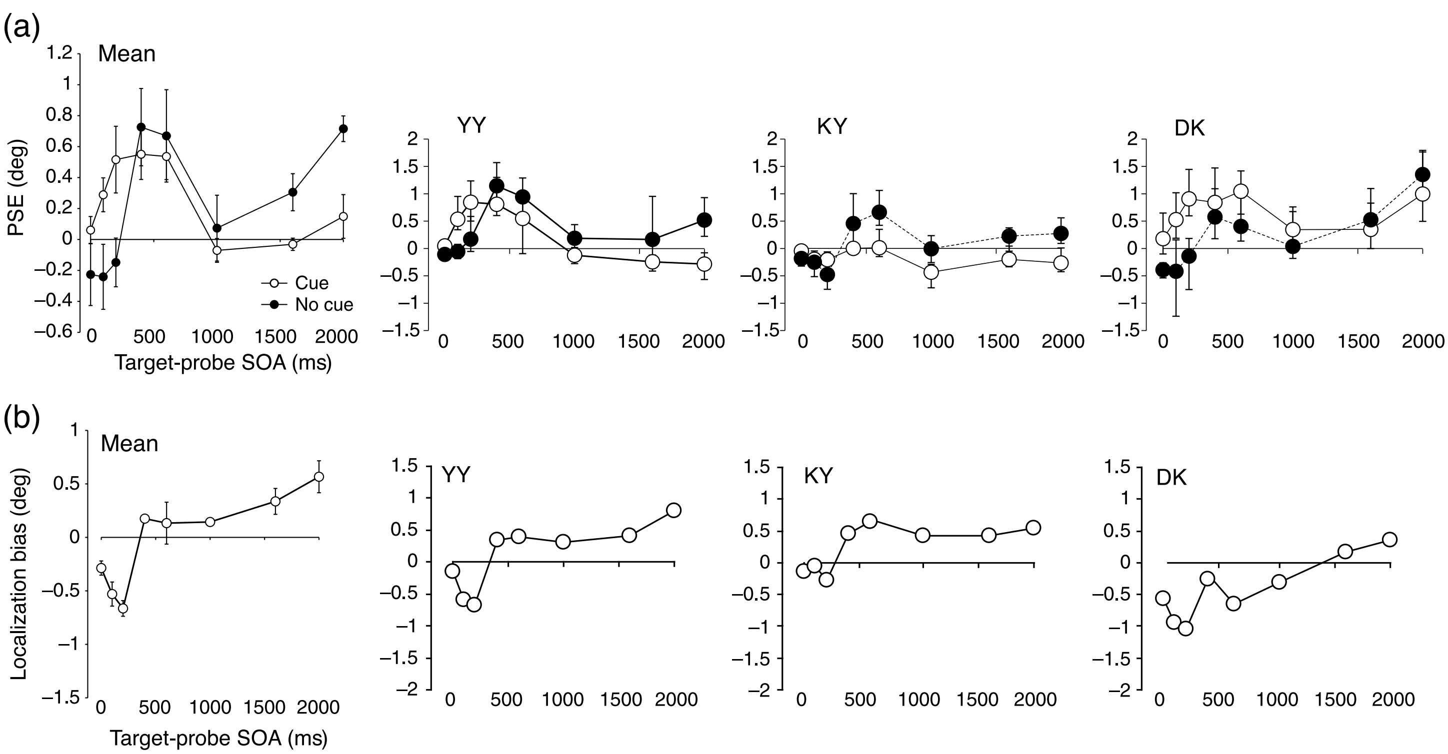

Figure 3. (a) Estimated PSE for each condition in Experiment 2. Mean and individual data are shown. Positive and negative values denote foveal and peripheral mislocalizations, respectively. Error bars indicate within-subject standard errors of the mean. (b) Localization biases in Experiment 2. Mean and individual data are shown. Positive and negative values denote attraction toward the cue and repulsion from the cue, respectively. Error bars indicate within-subject standard errors of the mean.

Simple main effects analyses of the interaction indicated that, in the 100- and 200-ms conditions, the target in the cue condition was significantly displaced more foveally than that in the no-cue condition (100 ms: $F(1, 16) = 5.37$, MSE = 0.078, $p < 0.04$; 200 ms: $F(1, 16) = 8.44$, MSE = 0.078, $p < 0.02$). Moreover, in the 2000-ms condition, the target in the cue condition was significantly displaced more peripherally than that in the no-cue condition ($F(1, 16) = 6.14$, MSE = 0.078, $p < 0.03$).

Discussion

In Experiment 2, we aimed at precise testing of the effect of the target–probe SOA on attentional repulsion and attentional attraction with the eight target–probe SOAs. Considering the results of Experiment 1, attentional repulsion would disappear at the target–probe SOA shorter than 550 ms, and attentional attraction would appear at the target–probe SOA longer than 1250 ms (Figure 2). As a result, there was a similar tendency as in Experiment 1, that is, attentional repulsion and attentional attraction were observed at short and long target–probe SOAs, respectively (Figure 3b). Specifically, in this experiment, we found that attentional repulsion was most prominent at the target–probe SOA of 100 and 200 ms. Moreover, the results also suggested that attentional attraction lasted at least until the target–probe SOA of 2000 ms.

Moreover, the results of the no-cue condition showed an interesting temporal course of foveal bias. In Experiment 2, foveal bias first peaked at the target–probe SOA of about 500 ms, disappeared at 1000 ms, and then resurged at 2000 ms. Inconsistently, however, in Experiment 1 foveal bias was observed in both the target–probe SOAs of 550 ms and 1250 ms. As Figure 3a shows, there was an individual difference in the temporal course of foveal bias. In particular, the steep increase in the mean results after the target–probe SOA of 1000 ms mainly stemmed from one observer's data, though other two observers also exhibited moderate increases of foveal bias. On the other hand, all observers showed a common peak of foveal bias at the target–probe SOA of 400 ms, and then foveal bias sharply decreased at the target–probe SOA of 1000 ms. At this stage, we cannot identify the critical factors causing the peak and valley in the magnitude of foveal bias. On the other hand, this peak and valley in the magnitude of foveal bias was common among observers and can be considered as a new temporal aspect of foveal bias that has not previously been reported.

Experiment 3

In this experiment, we aimed at testing the effects of the cue–target SOA as well as the target–probe SOA on attentional repulsion and attentional attraction. In the attentional repulsion literature, it is suggested that the repulsive position shift is caused by the attentional modulation of sensory location information (Arnott & Goodale, 2006; Suzuki & Cavanagh, 1997). Similarly, previous studies suggested that attentional attraction is due to the attentional modulation of location information in memory (Yamada et al., 2008). Although a previous study showed that the magnitude of attentional repulsion altered depending on the cue–target SOA due to the time course of attention shift (Suzuki & Cavanagh, 1997), it is unclear whether the magnitude of attentional attraction is also altered with the cue–target SOA. If attentional attraction is related to attention (Yamada et al., 2008), attentional attraction will also be affected by the cue–target SOA. Hence, we simultaneously manipulated cue–target SOAs and target–probe SOAs. We used five types of cue–target SOA: 50, 200, 1000, and 1500 ms and no cue. At the same time, we employed three types of target–probe SOAs: 0, 500, and 2000 ms. Repulsive and attractive position shifts were confirmed at the first and third SOAs, with no position shift at the second SOA in Experiment 2.

Methods

Observers

Two of the authors (YY and TK) and one naive observer (KY) participated in Experiment 3. All had normal or corrected-to-normal visual acuity.

Apparatus, stimuli, and procedure

The apparatus, stimuli, and procedure used in Experiment 3 were identical to Experiment 1 except for the following: The SOA between a cue and a target was varied (50, 200, 1000, and 1500 ms and no cue). Moreover, we employed the target–probe SOA of the 0-, 500-, and 2000-ms conditions. Trials were blocked with respect to each combination of a cue–target SOA and a target–probe SOA. Consequently, there were 15 blocks in total. A block consisted of seven (for the 0-ms target–probe SOA condition) or 13 horizontal positions (for the other target–probe SOA conditions), two visual fields (right and left), and 10 repetitions. Hence, observers performed 3300 trials in total, and completion of the trials took approximately 3 h for each observer.

Results

As in Experiment 1, we calculated the PSE and localization bias from the data of Experiment 3 (Figure 4). As shown in Figure 4a, target localization in all the cue–target SOA conditions changed in parallel with each other except for the cue–target SOA of 1500 ms. Among the cue–target SOA conditions, only at the 50-ms cue–target

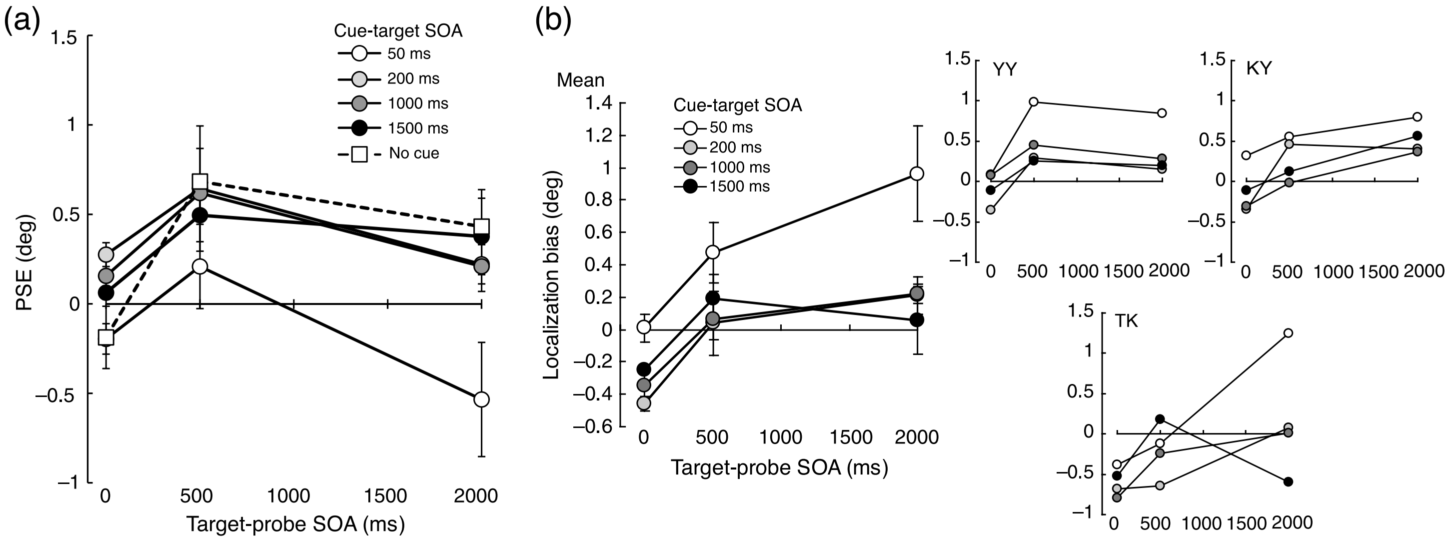

Figure 4. (a) Mean estimated PSE across observers for each condition in Experiment 3. Positive and negative values denote foveal and peripheral mislocalizations, respectively. Error bars indicate within-subject standard errors of the mean. (b) Localization biases in Experiment 3. Mean and individual data are shown. Positive and negative values denote attraction toward the cue and repulsion from the cue, respectively. Error bars indicate within-subject standard errors of the mean.

SOA target localization was made more peripherally than the others, regardless of the target–probe SOAs. Moreover, at the 2000-ms target–probe SOA, target localization in the cue condition was directed more peripherally than in the no-cue condition when the cue–target SOA was shorter than 1000 ms. On the other hand, at the 0-ms target–probe SOA, target localization in the cue condition was directed more peripherally than in the no-cue condition when the cue–target SOA was longer than 200 ms. We calculated 95% confidence intervals by using a bootstrap method based on data from each cue condition at each target–probe SOA (Wichmann & Hill, 2001b). As a result, when the cue–target SOA was 200 ms, the PSE in the cue and no-cue conditions did not overlap with each other at the target–probe SOA of 0 ms for all observers and 2000 ms for one observer. This indicates significant differences between the cue and no-cue conditions ($p < 0.05$).

First, on the mean PSE, a two-way ANOVA with target–probe SOA (0, 500, and 2000 ms) and cue–target SOA (50, 200, 1000, and 1500 ms and no cue) as factors was performed. The ANOVA revealed a significant main effect of cue–target SOA ($F(4, 8) = 7.44$, MSE = 0.465, $p < 0.009$). However, the main effect of target–probe SOA and the interaction were not significant ($F(2, 4) = 3.25$, MSE = 0.324, $p > 0.14$; $F(8, 16) = 1.40$, MSE = 0.081, $p > 0.26$, respectively). Multiple comparisons using Ryan's method revealed that the PSE in the 50-ms cue–target SOA condition significantly shifted more peripherally than other cue–target SOA conditions (ps < 0.004). Second, on localization bias, a two-way ANOVA with target–probe SOA (0, 500, and 2000 ms) and cue–target SOA (50, 200, 1000, and 1500 ms) as factors revealed significant main effects of target–probe SOA ($F(2, 4) = 16.78$, MSE = 0.074, $p < 0.02$) and cue–target SOA ($F(3, 6) = 21.45$, MSE = 0.028, $p < 0.002$). The interaction was not significant ($F(6, 12) = 0.67$, MSE = 0.104, $p > 0.67$). Multiple comparisons using Ryan's method revealed that localization bias in the 0-ms target–probe SOA condition occurred more repulsively than in other target–probe SOA conditions (ps < 0.02). Furthermore, localization bias in the 50-ms cue–target SOA condition occurred more attractively than in other cue–target SOA conditions (ps < 0.0009).

Discussion

Consistent with Experiments 1 and 2, at the cue–target SOA of 200 ms we again obtained attentional repulsion and attentional attraction at the short (0 ms) and long (2000 ms) target–probe SOAs, respectively. As seen in Figure 4b, the pattern of the results was consistent for all observers. In particular, all of the observers showed a significant magnitude of attentional repulsion when the cue–target SOA was 200 ms and the target–probe SOA was 0 ms, consistent with previous studies (e.g., Suzuki & Cavanagh, 1997). A similar pattern was observed when the cue–target SOA was 1000 ms. Moreover, the main effects of the target–probe SOA and the cue–target SOA were significant, but not their interaction, suggesting that the target–probe SOA and the cue–target SOA independently affect target localization: Attentional repulsion and attentional attraction were susceptible to both the cue–target and target–probe SOAs.

At the 50-ms cue–target SOA, target localization shifted more peripherally on average than in other cue–target SOA conditions, suggesting that the attraction effect of the cue was larger when the cue and target were temporally close to each other. This issue will be discussed in the General discussion section.

General discussion

The present study was aimed at elucidating the temporal relationship between attentional repulsion (e.g., Pratt & Arnott, 2008; Suzuki & Cavanagh, 1997) and attentional attraction (Uddin et al., 2005; Yamada et al., 2008). In Experiment 1, using a relative judgment task, we manipulated the SOA between the target and probe from 0 ms to 1250 ms and showed the repulsion effect in the 0-ms condition and the attraction effect in the 1250-ms condition while there was no cue effect at the 550-ms condition. Experiment 2 showed that attentional repulsion occurred with relatively short SOA, and attentional attraction occurred when this SOA was increased. Obviously, the direction of mislocalization was reversed from a repulsive one to an attractive one, as a function of the increase of the retention interval. A retention interval greater than 600 ms was necessary for attentional attraction to occur. Experiment 3 showed that temporal courses of attentional repulsion were parallel with those of attentional attraction, indicating that the target–probe SOA and the cue–target SOA independently affected target localization.

Before discussing the specific mechanisms underlying attentional repulsion and attentional attraction, we have to consider whether the observers' eye movements affected the present results. Although the observers in this study were instructed to gaze at the fixation cross throughout the experiment, the pattern of observers' involuntary eye movements could have been different between trials with or without the cue, and the difference in eye movement patterns could have contributed to the repulsion and attraction effects. However, a previous study did not support the involvement of eye movements in attentional repulsion (Arnott & Goodale, 2006). Moreover, previous research has shown that attentional attraction did not stem from the bias of eye positions (Yamada et al., 2008). Thus, it is unlikely that eye movements affected the pattern of the present results, although there is room for examining the potential role of eye movements such as fixational eye movements on localization bias.

It is suggested that attentional repulsion and attentional attraction may occur at different stages of visual processing. In the 0-ms condition, the perceived locations of the target and probe were compared simultaneously. On the other hand, in the longer SOA conditions, the perceived location of the probe was compared with the target location in memory. Attentional repulsion may occur in the early stages of visual processing, in which the target location is coded, as suggested in a previous study (Suzuki & Cavanagh, 1997). In contrast, attentional attraction may occur in subsequent stages (i.e., in the memory process) where the spatial representation of the target is retained (Nelson & Chaiklin, 1980).

In this view, attention may play a different role in a localization mechanism across time. In the location coding stage, as suggested by Suzuki and Cavanagh (1997), the target's location signals are distributed in a bell-shaped curve with a peak at the retinotopic center of the target. The perceived target location is represented by the centroid of this distribution curve. The distribution curve of location signals is based on the activation of hypothetical location coding units that correspond to retinal positions. The activation of a location coding unit is the highest at the target location; hence, without attentional modulation, the perceived location of the target is consistent with the actual target location. When attention is directed to the cued location, attention suppresses the activation of location coding units over the surrounding areas of the cued location like a Mexican hat distribution (e.g., Müller, Mollenhauer, Rösler, & Kleinschmidt, 2005). This may cause a relatively greater activation of the target's location signals at a location that is distant from the cued location, resulting in mislocalization away from the cue, as discussed in Suzuki and Cavanagh. On the other hand, in the later stages after coding, the observer's attention might be engaged in integration of the memorized target location with an attended location. In a previous study, the attraction effect toward a non-target stimulus was greater when the non-target stimulus vanished before localization than when the non-target remained visible (Hubbard & Ruppel, 2000). This finding supports the notion that location information is averaged in memory.

How does the cue cause the attraction effect? We agree with the idea that attentional attraction is explained on the basis of "memory averaging." Previous studies on displacement of a static or moving target have suggested that displacement was due to averaging between locations of the target and a non-target (e.g., Freyd & Johnson, 1987; Hubbard, 1995a, 1995b; Hubbard & Ruppel, 2000). In a similar vein, we suggest that location information of an attended object is likely to be averaged with the location information of a target. A previous study also explained attentional attraction by the memory averaging of location information of a target and an attended object (Yamada et al., 2008). The larger attraction effect, when the cue–target SOA was 50 ms in Experiment 3, suggests that location information of the target tends to be encoded (or averaged) together with that of the salient cue, and this could cause a shift in the remembered location of the target toward the salient cue. Previous studies have shown that spatial landmarks or reference frames affected target localization (Bryant & Subbiah, 1994; Nelson & Chaiklin, 1980; Simmering, Peterson, Darling, & Spencer, 2008; Spencer, Simmering, & Schutte, 2006). Another previous study proposed that the presence of a non-target stimulus induced activation at its location in a spatial network representation (Hubbard, 1995b). Likewise, in our explanation, cue stimuli play a role as attractors of attention that modulate the averaging of location information between objects in memory.

As another interpretation of attentional attraction, the judgment itself for target location might be affected by the presence of attentional focus in the spatial vicinity of the target, without averaged representation of location information between a target and a salient object. As target–probe SOA increased, neural signals for target location probably became weaker, leading to ambiguous judgments for target location. Hence, the judgment of target location might be susceptible to the influence of other reliable information. In the cue condition, the target followed the peripheral cue that was salient and, hence, might have attracted the observers' attention. Thus, the location of attentional focus might work as a reliable source for the judgment of target location. In another stream of research, it has been suggested that a cued object was judged as salient compared with a non-cued object (Kerzel, Zarian, Gauch, & Buetti, 2010; Schneider & Komlos, 2008) and that observers reported the presence of the target at the cued location even though no target was actually presented at the location (Prinzmetal, Long, & Leonardt, 2008). Thus, it is possible that what affected the attractive target mislocalization in the present study might have been response bias toward the cued location. Future studies should clarify which interpretation is suitable for attentional attraction: Averaged location information between a target and a salient object or response bias of target location toward the cue.

The present experiments showed the repulsion effect when the target–probe SOA was shorter, supporting the notion that attentional repulsion occurs at an early position-coding stage. As suggested by previous research, the repulsion effect may depend on the attentional modulation of the distribution of position-coding neural units at the early, retinotopic visual areas (Suzuki & Cavanagh, 1997). Pratt and Turk-Browne (2003) claimed that attentional repulsion occurs before the dorsal and ventral visual pathways split, because attentional repulsion was also found in action. Moreover, given that attentional repulsion is induced by an auditory cue (Arnott & Goodale, 2006), the superior colliculus and the parietal cortex, which govern spatial processing of both visual and auditory information (e.g., Bushara et al., 1999; Jay & Sparks, 1984), are additional candidates for the locus of the position-coding units. Thus, the neural basis of attentional repulsion is still under debate and awaits further investigation.

In sum, the present study investigated the temporal relationship between attentional repulsion and attentional attraction. This study revealed that the cue–target SOA and the target–probe SOA independently affected attentional repulsion and attentional attraction. The temporal course of the effect of the cue–target SOA was not altered by the target–probe SOA and vice versa. A previous study demonstrated that perceived visual information such as spatial frequency was preserved in short-term memory (Montaser-Kouhsari & Carrasco, 2009). In a similar vein, the present results suggest that a perceived location of the target was first encoded as a perceptual space representation and it was maintained in memory at least for 2000 ms. That is, attention-induced perceptual distortion of space (i.e., attentional repulsion) is preserved in memory but is subject to further attention-induced distortion specific to mnemonic spatial representation (attentional attraction).

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Corresponding author: Yuki Yamada.
Email: yamadayuk@gmail.com.
Address: Faculty of Human-Environment Studies, Department of Behavioral and Health Sciences, Kyushu University, 6-19-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan.

Footnotes

[1]The reason we presented a target in the upper visual field is that we wanted to investigate patterns of mislocalization of the target with high spatial uncertainty. Considering a previous study showing that spatial resolution was lower in the upper visual field than in the lower visual field (Talgar & Carrasco, 2002), it was desirable that the target was presented in the upper visual field in the experiments of the present study. Moreover, for reasons similar to the one raised above, the vertical target–probe array was not presented across the fixation cross but in peripheral visual fields. The first was to increase stimulus eccentricity. The second was to avoid a categorical coding of target locations that the target was seen at either the left or the right of the fixation cross.

[2]The suitable number of steps of the stimuli for each condition in Experiment 1 was determined by a preliminary observation conducted in advance. We employed a

different number of steps for each condition (7 steps for the 0-ms condition vs. 13 steps for the 550- and 1250-ms conditions) to cope with the increase of spatial uncertainty at long retention intervals (Sheth & Shimojo, 2001, 2004), that is, in the 1250-ms condition in our case.

[3]The cumulative probability estimate greater than 95% denotes that the fit is inappropriate (see Wichmann & Hill, 2001a for details).

[4]Ryan's method adopts the nominal significance level α' given as follows: $\alpha' = 2\alpha \,/\, (n * (m - 1))$, where α indicates the whole significance level, n indicates the number of groups to be compared, and m indicates the distance defined as the number of groups X_p satisfying $X_i \leq X_p \leq X_j$. Here, X_i and X_j are a pair in the hypothesis of concern. The degrees of freedom in this method depend on the degrees of freedom for the error term of the main effect or the simple main effect that includes the comparisons of concern.

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