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Representational momentum contributes to motion induced mislocalization of stationary objects

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The influence of a moving target on memory for the location of a briefly presented stationary object was examined. When the stationary object was aligned with the final portion of the moving target's trajectory, memory for the location of the stationary object was displaced forward (i.e., in the direction of motion of the moving target); the magnitude of forward displacement increased with increases in the velocity of the moving target, decreased with increases in the distance of the stationary object from the final location of the moving target, and increased and then decreased with increases in retention interval. It is suggested that forward displacement in memory for a stationary object aligned with the final portion of a moving target's trajectory reflects an influence of representational momentum of the moving target on memory for the location of the stationary object. Implications of the data for theories of representational momentum and motion induced mislocalization are discussed.

Memory for the final position of a previously-viewed moving target is often displaced forward in the direction of target motion, and this has been referred to as *representational momentum* (e.g., Freyd & Finke, 1984; for review, see Hubbard, 2005). Although there have been numerous studies of the influence of a nearby stimulus on the representational momentum of a moving target (e.g., Gray & Thornton, 2001; Hubbard, 1993, 1995a; Hubbard & Ruppel, 1999; Kerzel, 2002, 2003; Müsseler, Stork, & Kerzel, 2002; Whitney & Cavanagh, 2002), there have been far fewer studies of the influence of the representational momentum of a moving target on memory for a nearby stimulus. However, research not directly examining representational momentum has found that the presence of a moving target can influence localization of nearby stimuli (e.g., Durant & Johnston, 2004;

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Whitney & Cavanagh, 2000). Such an influence of the motion of a moving target on localization will be referred to as *motion induced mislocalization*. It is possible that the representational momentum of a moving target contributes to motion induced mislocalization of a nearby stationary object, and this possibility is examined in the studies reported here.

Several studies have suggested that location information for moving stimuli is processed differently than is location information for stationary stimuli (e.g., Eagleman & Sejnowski, 2000; Purushothaman, Patel, Bedell, & Ogmen, 1998; Whitney, Murakami, & Cavanagh, 2000). However, Whitney and Cavanagh (2000) suggested that influences of a moving target on localization of a stationary target reflect a more general mechanism that processes location information of moving stimuli and of stationary stimuli. In their study, Whitney and Cavanagh presented a rotating radial grating, and two physically aligned flashes were presented on opposite sides of the grating. Observers judged whether the flash on the right side of the grating appeared higher or lower than the flash on the left side of the grating, and the perceived positions of the flashes were displaced in the direction of the rotation of the grating. A similar misalignment in the perceived location of stationary flashes was found when observers viewed flashes on opposite sides of a linear translating grating, and the magnitude of perceived misalignment remained constant with increasing eccentricity of the flashes. Whitney and Cavanagh suggested that the influence of motion on localization was not limited to just the moving stimulus, and that localization of stationary stimuli was coded by mechanisms sensitive to motion.

Durant and Johnston (2004) presented stationary lines located on opposite sides of a rotating bar or along an arc on either side of two columns of vertically moving gratings. The stationary lines appeared to be mislocalized in the direction of the moving stimulus, and this was consistent with Whitney and Cavanagh (2000). Additionally, Durant and Johnston also reported that mislocalization in the relative location of the stationary stimuli increased with increases in the velocity of the moving stimulus and was stronger when the stationary stimuli were closer to the moving stimulus. Mislocalization of the stationary stimuli decreased when background flicker was introduced, and Durant and Johnston suggested that this demonstrated the contribution of motion to mislocalization (as flicker interfered with perception of motion). When eccentricity of the stationary stimulus was kept constant, mislocalization decreased as the distance of the stationary stimulus from the moving stimulus increased. Durant and Johnston suggested that mislocalization of the stationary stimuli was due to low-level local mechanisms and reflected feedback to primary visual cortex from motion selective cells in extrastriate cells that have receptive fields overlapping the retinal location of the stationary object.

Unlike Durant and Johnston (2004), Watanabe, Nijhawan, and Shimojo (2002) suggested that mislocalization occurred because location and motion signals were integrated at a relatively high level. In Watanabe et al., observers viewed through a vertical rectangular slit the motions of two vertically separated and horizontally moving diamond shapes. The diamonds moved in opposite directions (i.e., one leftward and one rightward), and when the diamonds were vertically aligned within the slit, two vertical white bars (one within each diamond) were briefly shown. After viewing the stimulus sequence, observers indicated the horizontal location of each of the bars relative to a central fixation point, and then indicated the direction of the top and bottom diamonds. The location of a given bar was mislocalized in the direction of the perceived motion of the diamond containing that bar, even when stimuli were viewed through a very narrow slit in which movement of the diamonds could not have been perceived. Watanabe et al. interpreted this as suggesting that mislocalization of the bars reflected perceived or illusory motion rather than physical motion, and hence involved high-level mechanisms.

Munger and Owens (2004) presented a flashed stationary object aligned with the orientation of a rotating target, 1 degree behind the orientation of the rotating target, or 1, 2, 3, or 4 degrees in front of the orientation of the rotating target. If the target continued to rotate after the stationary object vanished, then observers were more likely to judge that a stationary object located in front of the orientation of the rotating target was aligned with the target. However, if the target vanished at the same time that the stationary object vanished, then observers were not more likely to judge that a stationary object in front of the orientation of the rotating target was aligned with the target. Munger and Owens suggested that the greater likelihood of a judgement of "aligned" for stationary objects in front of the orientation of the target when the target continued to rotate after the stationary object vanished was consistent with a flash-lag effect (a mislocalization in which a briefly presented stationary object aligned with a moving target is judged to lag behind that moving target; for reviews, see Krekelberg & Lappe, 2001; Nijhawan, 2002). Such an explanation is consistent with findings that a flash-lag effect does not occur unless the moving target continues in motion after the flashed object vanishes (e.g., as in Brenner & Smeets, 2000).

The direction of displacement in motion-induced mislocalization of a stationary object appears consistent with the direction of displacement of a moving target attributed to representational momentum. If Whitney and Cavanagh (2000) are correct that a more general mechanism processes information regarding both stationary stimuli and moving stimuli, then it is possible that information regarding the motion (and representational momentum) of a moving stimulus might influence information regarding the location of a nearby stationary stimulus (and lead to motion-induced mislocalization of that stationary stimulus). In order to test this notion, the studies reported here manipulated variables known to influence representational momentum (e.g., target velocity, retention interval), and effects of those manipulations on judgements of the location of a stationary object were examined. In addition to providing further data on motion-induced mislocalization of a stationary object, the studies presented here explicitly consider the influence of representational momentum of a moving target on a nearby stationary object, and so complement previous studies of the influence of a nearby stationary object on representational momentum for a moving target.

Whitney and Cavanagh (2000), Durant and Johnston (2004), and Munger and Owens (2004) all examined perceived alignment; Whitney and Cavanagh and Durant and Johnson focused on alignment of two flashed lines on opposite sides of a moving stimulus, and Munger and Owens focused on alignment of a flashed line and a rotating bar. Similarly, Watanabe et al. (2002) examined the alignment between vertical lines and a fixation point. Such a focus on alignment involves judgement of the perceived configuration of multiple stimuli. In contrast, the studies reported here involved judgement of the remembered location of a single stimulus. Also, Whitney and Cavanagh, Durant and Johnston, and Munger and Owens presented smooth motion, but findings of Watanabe et al. suggest that smooth motion is not necessary in order for motion-induced mislocalization of the location of a stationary object to occur. Representational momentum occurs with both smooth motion (e.g., Hubbard, 1990) and with implied motion (e.g., Munger, Solberg, Horrocks, & Preston, 1999). Therefore, if representational momentum contributes to motion-induced mislocalization of a stationary target, then displacement in remembered location of a stationary object should occur when a nearby target exhibits implied motion, and that displacement should be consistent with the direction of target motion.

EXPERIMENT 1

In this experiment, a moving target exhibited leftward or rightward implied motion, and a stationary object was presented during the final portion of target motion. The stationary object was the same shape and size as the moving target, horizontally aligned with the final location of the moving target, and above or below the final location of the moving target. The moving target and the stationary object vanished at the same time and, after a brief retention interval, a stationary probe was presented. The probe was presented at the same vertical coordinates as the stationary object, and was slightly behind the horizontal coordinates of the stationary object, aligned with the horizontal coordinates of the stationary object, or slightly in front of the horizontal coordinates of the stationary object. Observers judged whether the probe was at the same location as the previously presented stationary object, and a comparison of probabilities of *same* responses to probes at different locations allowed examination of whether memory for the stationary object was systematically displaced.

Method

Participants. The participants were 15 undergraduate observers from the Texas Christian University who participated for partial course credit and were naïve to the hypotheses.

Apparatus. The stimuli were displayed upon and the data collected by an Apple iMac desktop computer equipped with a 15-inch colour monitor.

Stimuli. The moving target and stationary object were square shapes 20 pixels (approximately 0.83 degrees of visual angle) in width and in height. The moving target was a filled black square, and the stationary object was a black outline square with a white interior; all stimuli were presented against a white background. On each trial, there were five successive presentations of the target that implied either consistent rightward motion of the target or consistent leftward motion of the target, and consistent with previous representational momentum literature, these are referred to as *inducing stimuli*. As shown in Figure 1, each inducing stimulus was presented for 250 ms, and there was a 250 ms ISI between successive inducing stimuli. For rightward motion, the first inducing stimulus appeared approximately midway between the left side and the centre of the display, and the horizontal coordinates of each successive inducing stimulus were located 40 pixels (approximately 1.66 degrees of visual angle) to the right of the previous inducing stimulus; for leftward motion, the first inducing stimulus appeared approximately midway between the right side and the centre of the display, and the horizontal coordinates of each successive inducing stimulus were located 40 pixels to the left of the previous inducing stimulus. The vertical coordinates of the inducing stimuli were approximately centred along the vertical axis. The stationary object appeared when the final inducing stimulus appeared, and vanished when the final inducing stimulus vanished (and so the stationary object was displayed for 250 ms); by having the stationary object appear and vanish when an inducing stimulus appeared or vanished, the possibility that the stationary object could be misperceived as a subsequent inducing stimulus should be diminished. When the stationary object was presented above the inducing stimuli, the bottom of the stationary object was 20 pixels above the top of the final inducing stimulus; when the stationary object was presented below the inducing

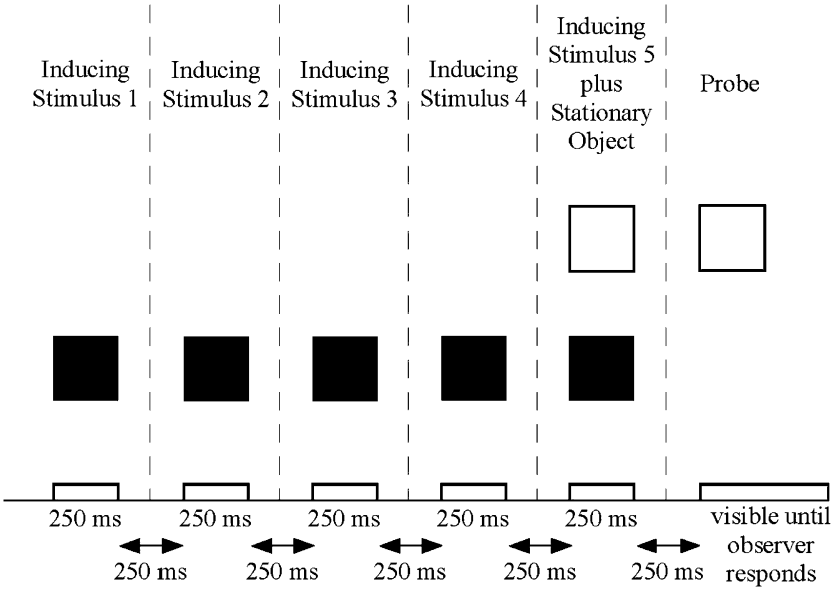

Figure 1. The structure of a trial in Experiment 1. There were five inducing stimuli; each inducing stimulus was presented for 250 ms, and there was a 250 ms ISI between successive inducing stimuli. The stationary object was presented at the same time as the fifth inducing stimulus. The probe was presented after a retention interval of 250 ms, and remained visible until the observer responded.

stimuli, the top of the stationary object was 20 pixels below the bottom of the final inducing stimulus. The probe was a black outline square with a white interior and was the same size as the stationary object. The probe was presented at the same vertical coordinates as the stationary object, and was located at one of seven horizontal positions relative to the stationary object: -9, -6, -3, 0, $+3$, $+6$, or $+9$ pixels. Probe positions denoted by a minus sign indicated that the probe was backward (i.e., shifted in the direction opposite to motion of the moving target) from the previous location of the stationary object by the indicated number of pixels, and probe positions denoted by a plus sign indicated that the probe was forward (i.e., shifted in the direction of motion of the moving target) from the previous location of the stationary object by the indicated number of pixels; the zero probe position was the same as the previous location of the stationary object. Each participant received 112 trials (7 probes [-9, -6, -3, 0, $+3$, $+6$, $+9$] $\times$ 2 directions [leftward, rightward] $\times$ 2 heights [above, below] $\times$ 4 replications) in a different random order.

Procedure. Observers were first given a practice session consisting of 10 practice trials that were randomly drawn from the experimental trials.

Observers initiated each trial by pressing a designated key. The inducing stimuli were presented, and the stationary object was visible during the presentation of the final inducing stimulus. The retention interval between the disappearance of the final inducing stimulus and the stationary object and the subsequent appearance of the probe was 250 ms. After the probe appeared, observers pressed a key marked *S* or a key marked *D* to indicate if the location of the probe was the same as or different from the location of the stationary object. Observers then initiated the next trial.

Results

The probabilities of a *same* response for each probe position are shown in Figure 2. Consistent with several studies in the representational momentum literature (e.g., Freyd & Jones, 1994; Hubbard, 1993; Munger & Minchew, 2002), estimates of the direction and magnitude of displacement in remembered location were determined by calculating the arithmetic weighted mean (i.e., the sum of the products of the proportion of *same* responses and the distance of the probe from the location of the stationary object, in pixels, divided by the sum of the proportions of *same* responses) for each observer for each condition. The sign of the weighted mean indicated that the direction of displacement (i.e., a minus sign indicated backward displacement in the direction opposite to motion of the moving target, a plus sign indicated forward displacement in the direction of motion

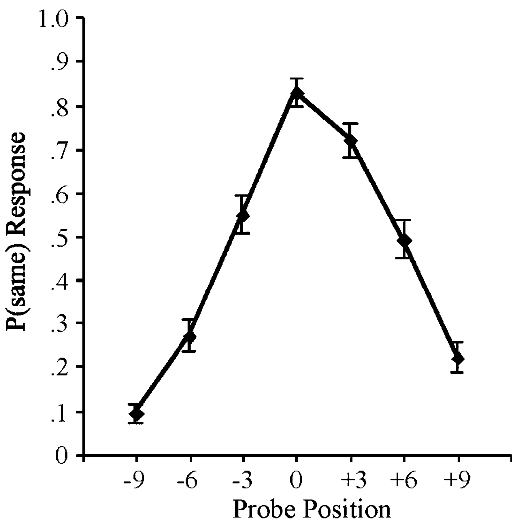

Figure 2. The probability of a *same* response in judgements of the location of the stationary object as a function of probe position in Experiment 1. Error bars reflect the standard error of the mean.

of the moving target), and the absolute value of the weighted mean indicated the magnitude of displacement (i.e., larger absolute values indicated larger magnitudes of displacement). The average weighted mean for each observer ($M = 0.95$) was significantly larger than zero, $t(14) = 3.61$, $p < .002$.

Discussion

An average weighted mean significantly larger than zero indicated that memory for the location of a stationary object was displaced forward (i.e., in the direction of motion of the moving target) of the actual location of that stationary object. The data from Experiment 1 are consistent with the direction of representational momentum of the moving target, and are consistent with the hypothesis that representational momentum of the moving target influenced judgements of the location of the stationary object. In judgements of alignment of stationary stimuli in Whitney and Cavanagh (2000) and in Durant and Johnston (2004), the moving stimulus was considerably larger than the stationary stimuli and was interposed between the stationary stimuli. However, in Experiment 1, the moving target was the same size and shape as the stationary object and was located to one side of a single stationary object. Thus, motion-induced mislocalization of a stationary stimulus can occur with a wider range of stimuli than previously demonstrated, and it is not necessary to interpose motion between stationary stimuli or require the moving stimulus to occupy a significantly larger portion of the visual field than is occupied by the stationary stimulus. More importantly, Experiment 1 demonstrated that motion-induced mislocalization can occur in a memory task, whereas previous studies demonstrated motion-induced mislocalization in perceptual tasks.

EXPERIMENT 2

If the representation (and representational momentum) of the moving target influences the representation of the stationary object, then the magnitude of forward displacement of the stationary object should be similar to the magnitude of forward displacement of the moving target. However, if displacement of the stationary object results from a source other than representational momentum of the moving target, then the magnitude of forward displacement of the stationary object would not necessarily be similar to the magnitude of forward displacement of the moving target. Accordingly, in Experiment 2, the stationary object and moving target were the same as in Experiment 1, but the probe was for the location of the stationary object or for the final location of the moving target. Observers were not cued prior to the appearance of the probe on a given trial whether the probe on that trial would be for the location of the stationary object or for the final location of the moving target.

Participants. The participants were 14 naïve undergraduate observers drawn from the same participant pool as in Experiment 1, and none had participated in the previous experiment.

Apparatus. The apparatus was the same as in Experiment 1.

Stimuli. The stimuli were the same as in Experiment 1, with the following exceptions: Probes for the stationary object were black outline squares 20 pixels in width, vertically aligned with the stationary object and horizontally offset from the stationary object by −9, −6, −3, 0, +3, +6, or +9 pixels (just as in Experiment 1); probes for the moving target were filled black squares 20 pixels in width, vertically aligned with the final inducing stimulus and horizontally offset from the final inducing stimulus by −9, −6, −3, 0, +3, +6, or +9 pixels. Each participant received 224 trials (7 probes [−9, −6, −3, 0, +3, +6, +9] × 2 directions [leftward, rightward] × 2 heights [above, below] × 2 judgements [stationary object, moving target] × 4 replications) in a different random order.

Procedure. The procedure was the same as in Experiment 1, with the following exceptions: If the probe was for the stationary object, observers pressed a key marked *S* or a key marked *D* to indicate if the location of the probe was the same as or different from the location of the stationary object; if the probe was for the moving target, observers pressed a key marked *S* or a key marked *D* to indicate if the location of the probe was the same as or different from the final location of the moving target.

Results

The probabilities of a *same* response for each probe position for stationary objects and for moving targets are shown in Figure 3. The weighted mean estimates of displacement were calculated as in Experiment 1. A paired *t*-test revealed that no differences between the average weighted mean for stationary objects ($M = 0.60$) and the average weighted mean for moving targets ($M = 0.77$), $t(13) = 1.09$, $p > .29$. The average weighted means for stationary objects, $t(13) = 2.78$, $p < .02$, and for moving targets, $t(13) = 3.77$, $p < .003$, were significantly larger than zero.

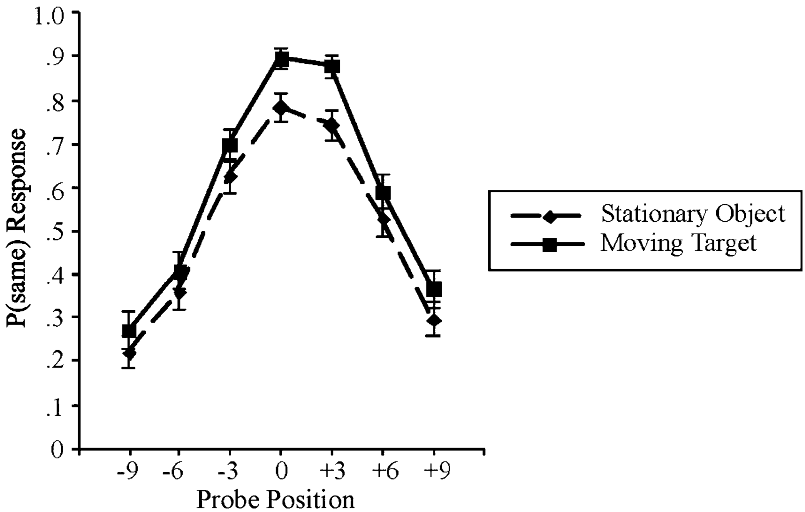

Figure 3. The probability of a *same* response in judgements of the location of the stationary object or moving target as a function of probe position in Experiment 2. Data for stationary objects are plotted with diamonds, and data for moving targets are plotted with squares. Error bars reflect the standard error of the mean.

Discussion

Memory for the location of a stationary object was displaced forward of the actual location of that stationary object, and this replicates the pattern observed in Experiment 1. Memory for the final location of the moving target was displaced forward of the actual final location of that moving target, and this replicates the standard representational momentum effect. Furthermore, the magnitude of forward displacement in memory for the location of stationary objects did not differ from the magnitude of forward displacement in memory for the final location of moving targets. The data from Experiment 2 are consistent with the hypothesis that the representation (and representational momentum) of the moving target influenced the representation of the stationary object (and contributed to motion induced localization). Inspection of Figure 3 suggests a higher average probability of a *same* response for moving targets than for stationary objects, and this probably reflects a greater uncertainty regarding the position of a moving target (displacement reflects the horizontal distance of the mean of the response distribution from the zero position, and not the vertical height of the response distribution).

EXPERIMENT 3

If forward displacement of a stationary object in Experiments 1 and 2 resulted from representational momentum of the moving target influencing the representation of that stationary object, then forward displacement of a similar stationary object should be influenced by variables previously shown to influence representational momentum of a moving target. One such variable is velocity, as faster velocities are usually linked with larger magnitudes of forward displacement (e.g., Freyd & Finke, 1985; Hubbard & Bharucha, 1988; Munger & Owens, 2004).[1] Accordingly, in Experiment 3, the stationary object and moving target were the same as in Experiment 1, but the velocity of the moving target varied across trials. If displacement in memory for the location of the stationary object in Experiments 1 and 2 resulted from representational momentum of the moving target influencing the representation of the stationary object, then memory for the location of a stationary object should exhibit a larger magnitude of displacement in the direction of target motion when the target moves at a faster velocity.

Participants. The participants were 14 naïve undergraduate observers drawn from the same participant pool as in Experiment 1, and none had participated in the previous experiments.

Apparatus. The apparatus was the same as in Experiment 1.

Stimuli. The stimuli were the same as in Experiment 1, with the following exceptions: Following Freyd and Johnson (1987), the velocity of implied motion was manipulated by varying the ISI between inducing stimuli, and the duration of each inducing stimulus was constant (250 ms) across velocities. For slow moving targets, the ISI was 500 ms, and for fast moving targets, the ISI was 250 ms. For both slow moving targets and fast moving targets, the retention interval between the disappearance of the final inducing stimulus and the stationary object and the subsequent appearance of the probe was 250 ms. Each participant received 224 trials (7 probes [-9, -6, -3, 0, $+3$, $+6$, $+9$] $\times$ 2 directions [leftward, rightward] $\times$ 2 heights [above, below] $\times$ 2 velocities [slow, fast] $\times$ 4 replications) in a different random order.

[1] The effect of target velocity is one of the most robust influences on displacement of a moving target in the direction of motion, although this effect is diminished (a) with increases in implied friction (Hubbard, 1995a), (b) if the target was initially stationary and its subsequent motion attributed to contact from a moving object (Hubbard & Ruppel, 2002), (c) at very high target velocities (Munger & Owens, 2004), and (d) for continuous motion visual targets when observers cannot track the target (Kerzel, Jordan, & Müsseler, 2001). However, none of these exceptions are relevant in the current design.

Procedure. The procedure was the same as in Experiment 1.

Results

The probabilities of a *same* response for each probe position for stationary objects accompanied by slow moving targets and for stationary objects accompanied by fast moving targets are shown in Figure 4. The weighted mean estimates of displacement were calculated as in Experiment 1. A paired t-test revealed that the average weighted mean for stationary objects accompanied by fast moving targets ($M = 0.99$) was significantly larger than the average weighted mean for stationary objects accompanied by slow moving targets ($M = 0.65$), $t(13) = 2.27$, $p < .05$. The average weighted means for stationary objects accompanied by slow moving targets, $t(13) = 4.20$, $p < .001$, or by fast moving targets, $t(13) = 4.13$, $p < .001$, were significantly larger than zero.

Discussion

Memory for the location of a stationary object was displaced forward of the actual location of that stationary object, and this replicates the pattern

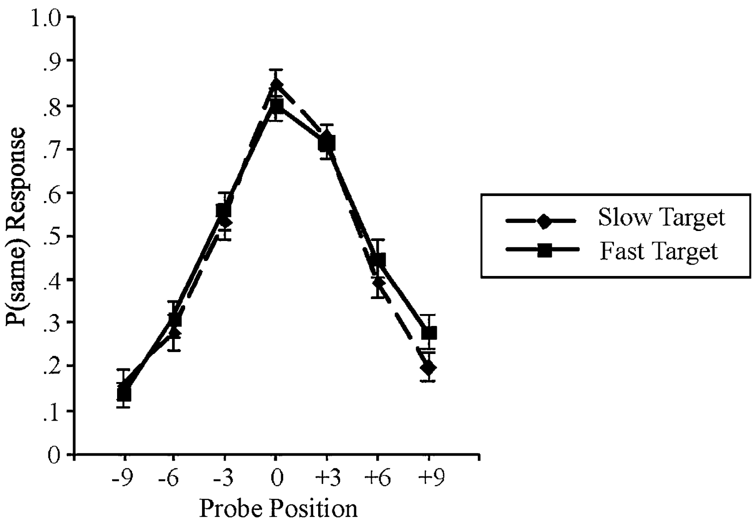

Figure 4. The probability of a *same* response in judgements of the location of the stationary object as a function of probe position in Experiment 3. Data for stationary objects accompanied by slow moving targets are plotted with diamonds, and data for stationary objects accompanied by fast moving targets are plotted with squares. Error bars reflect the standard error of the mean.

observed in Experiments 1 and 2. Furthermore, a fast moving target resulted in a larger magnitude of forward displacement in memory for the location of the stationary object than did a slow moving target, and this is consistent with the effect of velocity on forward displacement of moving targets previously reported. This velocity effect is not immediately obvious in Figure 4, but can be seen in the slightly steeper drop-off in the probability of a *same* response to positive probe positions for stationary objects accompanied by slow moving targets than to positive probe positions for stationary objects accompanied by fast moving targets. The effect of target velocity on displacement of stationary objects in Experiment 3 is consistent with the hypothesis that representational momentum from the moving target influenced memory for the location of the stationary object. The duration and location of stationary objects were constant across differences in target velocity, and so larger displacement of stationary objects when those objects were accompanied by fast moving targets was due to properties of the target and target motion and not due to differences in the duration or location of stationary objects.

EXPERIMENT 4

Another variable that influences representational momentum of a moving target is retention interval, as the magnitude of forward displacement increases during the first few hundred milliseconds after a moving target vanishes and decreases after several hundred milliseconds (Freyd & Johnson, 1987; for discussion, see Hubbard, 2005). If displacement in memory for the location of the stationary object in Experiments 1, 2, and 3 resulted from representational momentum of the moving target, then displacement for a similar stationary object should exhibit a time course similar to the time course of representational momentum. Accordingly, in Experiment 4, the stationary object and moving target were the same as in Experiment 1, but the retention interval between the disappearance of the final inducing stimulus and the appearance of the probe varied across trials. If displacement in memory for the location of the stationary object in Experiments 1, 2, and 3 resulted from the representation (and representational momentum) of the moving target influencing the representation of the stationary object, then displacement of the stationary object should increase during the first few hundred milliseconds after the stationary object and moving target vanish and then decline.

Participants. The participants were 14 naïve undergraduate observers drawn from the same participant pool as in Experiment 1, and none had participated in the previous experiments.

Apparatus. The apparatus was the same as in Experiment 1.

Stimuli. The stimuli were the same as in Experiment 1, with the following exceptions: The retention interval between the disappearance of the final inducing stimulus and the appearance of the probe was 50, 250, or 450 ms. Each participant received 252 trials (7 probes [−9, −6, −3, 0, +3, +6, +9] × 2 directions [leftward, rightward] × 2 heights [above, below] × 3 retention intervals [50, 250, 450] × 6 replications) in a different random order.

Procedure. The procedure was the same as in Experiment 1.

Results

The probabilities of a *same* response for each probe position for each retention interval are shown in Figure 5. The weighted mean estimates of displacement were calculated as in Experiment 1, and were analysed in a 2 (direction) × 2 (height) × 3 (retention interval) repeated measures ANOVA. Retention interval was significant, $F(2, 26) = 3.85$, $MSE = 0.40$, $p < .05$, and least squares comparisons revealed that forward displacement of stationary objects after a 250 ms ($M = 0.71$) retention interval was larger

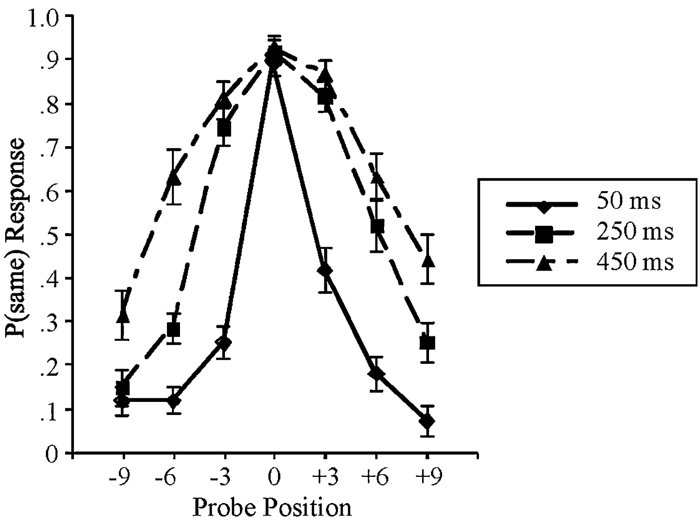

Figure 5. The probability of a *same* response in judgements of the location of the stationary object as a function of probe position in Experiment 4. Data for retention intervals of 50 ms are plotted with diamonds; data for retention intervals of 250 ms are plotted with squares, and data for retention intervals of 450 ms are plotted with triangles. Error bars reflect the standard error of the mean.

than forward displacement of stationary objects after a 50 ms ($M = 0.25$) or a 450 ms ($M = 0.41$) retention interval. No other main effects or interactions approached significance. The average weighted mean for stationary objects after a 250 ms retention interval, $t(13) = 3.50$, $p < .05$, was significantly larger than zero, whereas the average weighted means for stationary objects after a 50 ms, $t(13) = 1.05$, $p > .31$, or a 450 ms, $t(13) = 1.90$, $p > .07$, retention interval were not significantly different from zero.

Discussion

Memory for the location of a stationary object was displaced forward of the actual location of that stationary object when the retention interval was 250 ms, but memory for the location of a stationary object was not displaced from the actual location of that stationary object when the retention interval was 50 or 450 ms. This pattern is consistent with the time course of representational momentum reported by Freyd and Johnson (1987), and so the effect of retention interval on displacement of the stationary object in Experiment 4 is consistent with the hypothesis that the moving target (and representational momentum of the moving target) influenced memory for the location of the stationary object. Furthermore, the results of Experiment 4 suggest that motion-induced mislocalization of a stationary object, like representational momentum, is a dynamic process that changes across time. The effect of retention interval on motion-induced mislocalization of the stationary object suggests that displacement in the judged position of a stationary object involves memory and is not a purely perceptual phenomenon. Also, inspection of Figure 5 shows an increase in the likelihood of a *same* response with increases in retention interval, and this might reflect increases in uncertainty with increases in retention interval.

EXPERIMENT 5

Forward displacement in memory for the location of a moving target (i.e., representational momentum) has been suggested to result from spreading activation within a network representation of space in which there is greater activation for that region of the network corresponding to the target's anticipated trajectory (e.g., Erlhagen & Jancke, 2004; Hubbard, 1995b; Müsseler et al., 2002). Spreading activation weakens with increases in the distance that activation spreads (e.g., Anderson, 1983), and so if forward displacement of the stationary object results from spreading activation from the moving target, then forward displacement of the stationary object should decrease as the distance between the stationary object and the moving target increases. Although no difference between displacement of stationary objects and displacement of moving targets was observed in Experiment 2, stationary objects were quite close to moving targets, and a decrease in displacement of stationary objects might be observed if the distance between stationary objects and moving targets was increased. Accordingly, Experiment 5 presented the same stimuli as in Experiment 1, but the distance of the stationary object from the moving target varied across trials.

Participants. The participants were 15 naïve undergraduate observers drawn from the same participant pool as in Experiment 1, and none had participated in the previous experiments.

Apparatus. The apparatus was the same as in Experiment 1.

Stimuli. The stimuli were the same as in Experiment 1, with the following exceptions: The vertical distance between the stationary object and the moving target was 20, 60, or 100 pixels (approximately 0.83, 2.50, or 4.15 degrees of visual angle). Each participant received 252 trials (7 probes [-9, -6, -3, 0, $+3$, $+6$, $+9$] $\times$ 2 directions [leftward, rightward] $\times$ 2 heights [above, below] $\times$ 3 distances [20, 60, 100 pixels] $\times$ 4 replications) in a different random order.

Procedure. The procedure was the same as in Experiment 1.

Results

The probabilities of a *same* response for each probe position for stationary objects 20, 60, or 100 pixels distant from the moving target are shown in Figure 6. The weighted mean estimates of displacement were calculated as in Experiment 1, and were analysed in a 2 (direction) $\times$ 2 (height) $\times$ 3 (distance) repeated measures ANOVA. Distance was significant, $F(2, 28) = 4.61$, $MSE = 0.69$, $p < .02$, and least squares comparisons revealed that forward displacement of stationary objects 20 pixels ($M = 1.03$) distant was larger than forward displacement of stationary objects 60 pixels ($M = 0.62$) or 100 pixels ($M = 0.40$) distant. No other main effects or interactions approached significance. The average weighted mean was significantly greater than zero for stationary objects 20 pixels distant, $t(14) = 5.01$, $p < .001$, and 60 pixels distant, $t(14) = 3.26$, $p < .01$, but only marginally greater than zero for stationary objects 100 pixels distant, $t(14) = 2.04$, $p < .07$.

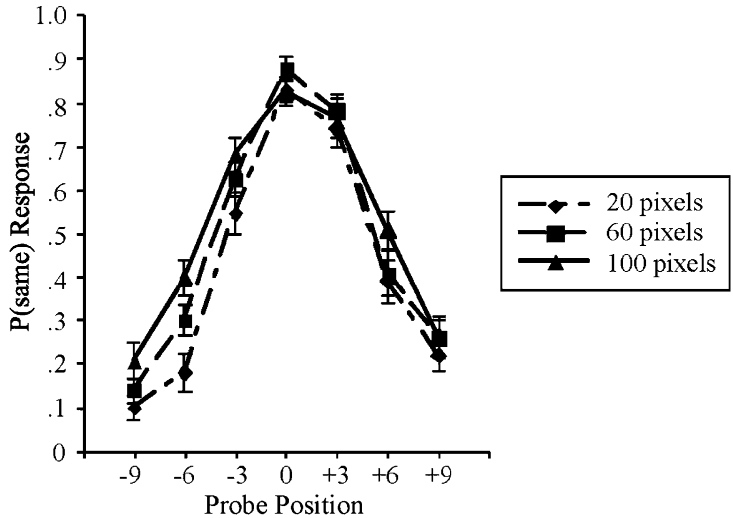

Figure 6. The probability of a *same* response in judgements of the location of the stationary object as a function of probe position in Experiment 5. Data for stationary objects 20 pixels from the moving target are plotted with diamonds; data for stationary objects 60 pixels from the moving target are plotted with squares, and data for stationary objects 100 pixels from the moving target are plotted with triangles. Error bars reflect the standard error of the mean.

Discussion

Memory for the location of a stationary object was displaced forward of the actual location of that stationary object, and this replicates Experiments 1, 2, 3, and the 250 ms condition of Experiment 4. Furthermore, forward displacement of stationary objects 20 pixels distant was significantly larger than forward displacement of stationary objects 60 pixels or 100 pixels distant (and there was a trend for stationary objects 60 pixels distant to exhibit larger displacement than did stationary objects 100 pixels distant). This pattern is consistent with hypotheses that (a) spreading activation from the representation of the moving target (that underlies representational momentum of the moving target) influenced the represented location of the stationary object, and (b) the strength of this spreading activation decreased with increases in the distance of the stationary target from the moving target. This pattern is also consistent with Durant and Johnston's (2004) finding of decreases in mislocalization with increases in the distance between stationary stimuli and moving stimuli. As shown in Figure 6, larger forward displacement for stationary objects closer to moving targets appears driven primarily by an increased ability of observers to reject negative probes when stationary objects were closer to moving targets, and this parallels Munger and Owens' (2004) finding of an increased ability of observers to reject negative probes for the final position of a target when a stationary object aligned with that final position was briefly presented.

EXPERIMENT 6

The results of Experiments 1, 2, 3, 4, and 5 are consistent with the possibility that representational momentum from a moving target influences the remembered location of a stationary object spatially and temporally aligned with the end of that target's trajectory. However, representational momentum from a moving target should not influence memory for a stationary object spatially and temporally aligned with an earlier portion of a target's trajectory, as by the time the moving target eventually vanishes and a probe is presented, any influence of representational momentum from the time such a stationary object was presented should have decayed. Accordingly, Experiment 6 presented the same inducing stimuli as Experiment 1, but the stationary object was spatially and temporally aligned with the middle of target motion. If forward displacement of the stationary object in Experiments 1, 2, 3, 4, and 5 was due to representational momentum from the moving target, then memory for a similar stationary object spatially and temporally aligned with the middle of target motion should not exhibit forward displacement. However, if forward displacement of the stationary object in Experiments 1, 2, 3, 4, and 5 was due to some factor other than representational momentum of the moving target, then memory for a stationary object aligned with the middle of target motion might still exhibit forward displacement.

Participants. The participants were 15 naïve undergraduate observers drawn from the same participant pool as in Experiment 1, and none had participated in the previous experiments.

Apparatus. The apparatus was the same as in Experiment 1.

Stimuli. The stimuli were the same as in Experiment 1, with the following exceptions: The stationary object appeared when the third inducing stimulus appeared and disappeared when the third inducing stimulus disappeared, and the stationary object was either 20 pixels above the third inducing stimulus or 20 pixels below the third inducing stimulus on each trial. The probe was presented at the same vertical coordinates as the stationary object, and was located at one of seven horizontal positions relative to the stationary object: -9, -6, -3, 0, $+3$, $+6$, or $+9$ pixels. Each participant received 112 trials (7 probes [-9, -6, -3, 0, $+3$, $+6$, $+9$] $\times$ 2 directions [leftward, rightward] $\times$ 2 heights [above, below] $\times$ 4 replications) in a different random order.

Procedure. The procedure was the same as in Experiment 1.

Results

The probabilities of a *same* response for each probe position are shown in Figure 7. The weighted mean estimates of displacement were calculated as in Experiment 1, and the average weighted mean ($M = -0.41$) did not differ from zero, $t(14) = -1.31$, $p > .21$.

Discussion

Memory for the location of a stationary object aligned with the middle of target motion was not significantly displaced forward from the actual location of that stationary object; indeed, there is a clear trend in the opposite direction. In conjunction with the results of Experiments 1–5, the results of Experiment 6 suggest that representational momentum for a moving target influences the remembered location of a stationary target aligned with the end of target motion, but does not influence (at least at the time the probe is presented) the remembered location of a stationary object aligned with an earlier portion of target motion. Inspection of Figure 7 suggests a higher average probability of a *same* response for stationary objects in Experiment 6 than in Experiments 1–5; this probably reflects a

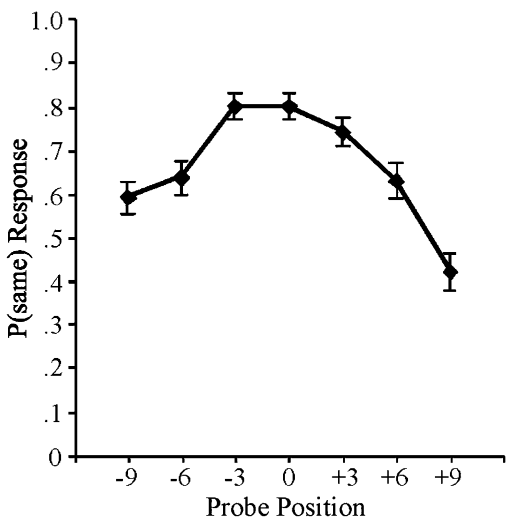

Figure 7. The probability of a *same* response in judgements of the location of the stationary object as a function of probe position in Experiment 6. Error bars reflect the standard error of the mean.

greater uncertainty regarding the position of the stationary object that results from the greater latency between the disappearance of the stationary object and the appearance of the probe in Experiment 6, and this is consistent with the higher probabilities of a *same* response with longer retention intervals shown in Figure 5 in Experiment 4. Interestingly, effects of the location of the stationary object relative to the moving target in the memory task in the current studies do not appear consistent with effects of the location of the stationary stimuli relative to the moving stimuli in the perception tasks in Durant and Johnston (2004) and Whitney and Cavanagh (2000), but the reasons for this are not entirely clear.

GENERAL DISCUSSION

Memory for the location of a stationary object briefly presented near the final location of a moving target and just prior to the moving target's disappearance was displaced in the direction of motion of that moving target. The magnitude of this displacement was larger when (a) the moving target moved at a faster velocity, (b) the stationary object was closer to the final location of the moving target, and (c) the retention interval was 250 ms. Such forward displacement in the remembered location of a stationary object is consistent with (a) previous findings that motion of a moving target can result in mislocalizations in the perceived location of nearby stationary stimuli, and (b) the possibility that the representation of the stationary object was influenced by the representational momentum of the moving target and, more specifically, that representational momentum for the moving target influenced memory for the location of a nearby stationary object. Given that representational momentum reflects (at least in part) operation of high-level mechanisms (for discussion, see Hubbard, 2005), an account of the displacement of the stationary object that is based upon representational momentum of the moving target would suggest that motion-induced mislocalization results (at least in part) from high-level mechanisms.

If motion-induced mislocalization in Experiments 1, 2, 3, 4, and 5 resulted from representational momentum of moving targets, then the magnitude of motion-induced mislocalization should be similar across different experimental conditions that evoke similar magnitudes of representational momentum. The distances of stationary objects from moving targets, velocity of moving targets, and retention interval in Experiment 1 were the same as in Experiment 2, the fast moving target condition in Experiment 3, the 250 ms condition in Experiment 4, and the 20 pixel condition in Experiment 5; therefore, the magnitude of motion-induced mislocalization of stationary objects should be similar in those five conditions. When weighted mean estimates of displacement from those conditions were entered into a one-way ANOVA with condition as a between-subjects factor, condition was not significant, $F(4, 67) = 0.69$, $MSE = 0.74$, $p > .60$. Similarity in motion-induced mislocalization when conditions predicted similar magnitudes of representational momentum, coupled with differences in motion-induced mislocalization when conditions predicted different magnitudes of representational momentum (e.g., differences in target velocity, distance between moving target and stationary object, and retention interval), support the claim that motion-induced mislocalization of stationary objects in Experiments 1, 2, 3, 4, and 5 resulted from representational momentum of moving targets.

Two alternative hypotheses for the forward displacement of the stationary object can be ruled out. First, forward displacement of the stationary object could not result from induced motion caused by the moving target. Such induced motion would be in the direction opposite to the direction of target motion, and would result in backward displacement rather than forward displacement. Second, forward displacement of the stationary object could not result from post-saccadic ocular drift in the direction of target motion after the moving target vanished. Observers did not receive explicit instructions regarding eye movements, and so they presumably tracked the targets by using a series of saccadic movements. In such cases, an observer's fixation could have drifted in the direction of saccadic movements after the target vanished. Given that targets are mislocalized toward the fovea (Müsseler, van der Heijden, Mahmud, Deubel, & Ertsey, 1999), forward displacement of the stationary object could then occur. However, post-saccadic ocular drift would presumably result in stimuli at all locations being similarly displaced, whereas Experiment 5 found that stationary objects further from the final location of the moving target did not exhibit as much displacement as did stationary objects closer to the final location of the moving target.

Why might the representation of a moving target influence the representation of a stationary object aligned with that moving target? If influences of a moving target on localization of a stationary object reflect a general mechanism that encodes both location and motion information (cf. Whitney & Cavanagh, 2000), then there are at least two possibilities. One possibility is that representations of moving targets are processed more quickly than are representations of stationary objects (e.g., Purushothaman et al., 1998; Whitney et al., 2000), and so an initially faster or stronger spreading activation in the direction of target motion from the moving target initially biases the subsequent representation of the stationary object in the direction of target motion. A second possibility is that the relatively briefer presentation of the stationary object results in a conjunction error in which the more strongly established motion signals from the moving target are bound to the stationary object as well as to the moving target. Such a speculation is consistent with the possibility that representational momentum is an elementary feature of moving targets, and extends models of feature integration that typically focus on visible properties by suggesting nonvisible features corresponding to forces and dynamics can also be bound to an object representation.

The notion of "motion-induced mislocalization" initially referred to displacement in the perceived or remembered location of a stationary object that was consistent with the motion of a nearby moving target. A broader usage of "motion-induced mislocalization" might refer to any mislocalization of a target that resulted from motion. In this broader usage, representational momentum could be considered a subset of motion-induced mislocalization in which the stimulus that is mislocalized is the stimulus that is in motion. Such a broader usage would be consistent with the notion that a more general mechanism codes both location and motion information, and would also be consistent with the notion that motion of a target might lead to perceived motion of a stationary object. Indeed, such perceived motion of a stationary stimulus has been reported, and has been referred to as *motion capture* (e.g., stationary dots superimposed on an apparent surface exhibiting apparent motion appear to move in the same direction as the apparent surface, Ramachandran, 1985; see also Bressan & Vallortigara, 1993; Festa-Martino & Welch, 2001). Exploration of potential connections between motion-induced mislocalization and motion capture remain for future research.

The experiments reported here suggest that the presence and proximity of a moving target influence judgements of the location of a nearby stationary object. The current studies complement previous research by showing such displacement is not limited to judgements of perceived relative alignment, but can also occur in judgements of remembered absolute position. Also, the current studies show that motion-induced mislocalization can result from implied motion of the moving target. The effects of target velocity, retention interval, and distance of the stationary object from the moving target are all consistent with the hypothesis that the displacement of the stationary object is influenced by representational momentum from the moving target. Representational momentum of the moving target influences the representation of the location of the stationary object, and this influence results in the representation of the location of the stationary object being displaced in ways consistent with the representational momentum of the moving target. This influence of the representational momentum of a moving target on memory for a nearby stationary object complements previous research showing a nearby stationary object or a larger surrounding frame can influence displacement of a moving target, and highlights the importance of context in the representation of location.

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