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Vision Research 45 (2005) 3253–3261

Vision Research

www.elsevier.com/locate/visres

Attentive tracking shifts the perceived location of a nearby flash ☆

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Received 20 December 2004; received in revised form 12 May 2005

Abstract

Several studies have shown that the perceived position of a briefly presented stimulus can be displaced by nearby motion or by eye movements. We examined whether attentive tracking can also modulate the perceived position of flashed static objects when eye movements and low-level motion are controlled. Observers attentively tracked two target bars 180° apart on a rotating, 12-spoke radial grating and judged the alignment of two flashes that were briefly presented, one on each side of the grating. Because of the symmetry of the 12-spoke grating, test flashes could be timed so that the rotating grating was always aligned to a standard orientation at the time of the test, while the tracked bars themselves, being only two of the 12 spokes, could probe locations that differed by multiples of 30° ahead of, aligned with, or behind, the test bars. Despite the physical identity of the stimulus in each test—same orientation, same motion—the perceived position of the two flashes strongly depended on the locus of attention: when the test flashes were presented ahead of the tracked bars, a large position shift in the direction of the grating's motion was seen. If they were presented behind the tracked bars, the illusory displacement was reduced or slightly reversed. These effects of attention led us to suggest an attentional model of position distortions that links the effects seen for motion and for eye movements.

Keywords: Position shift; Attentive tracking; High-level motion

1. Introduction

It is a challenging task for the visual system to accurately localize objects when the viewer, the viewer's eyes, and the objects in the scene may all be moving. Early visual areas from V1 to V4 and other higher areas, such as MT, maintain retinotopy (Fellman & Van Essen, 1991) that could provide a basis for localization. However, recent findings of position distortions caused by object motion and by eye movements show that factors more malleable than retinotopy must also be contributing to localization. For example, the position of a stimulus presented briefly just before or after a saccade or during smooth pursuit appears systematically displaced from its veridical position (for saccades: Cai, Pouget, Schlag-Rey, & Schlag, 1997; Deubel, Schneider, & Bridgeman, 1996; Deubel, Bridgeman, & Schneider, 1998; Lappe, Awater, & Krekelberg, 2000; Matin, 1972; Ross, Morrone, & Burr, 1997; for smooth pursuit: Mateeff & Hohnsbein, 1988; Mitrani & Dimitrov, 1982; Van Beers, Wolpert, & Haggard, 2001; see Ross, Morrone, Goldberg, & Burr, 2001; Schlag & Schlag-Rey, 2002 for review). Independently of eye movements, an object's motion can also shift the perceived position of an adjacent stationary stimuli in the direction of motion, and can shift judgments of the position of the moving object itself, also in the direction of the motion (DeValois & DeValois, 1991; Fröhlich, 1923; Nijhawan, 1994; Ramachandran & Anstis, 1990; Whitney & Cavanagh, 2000; see Krekelberg & Lappe, 2001; Njhawan, 2002; Whitney, 2002 for reviews). These studies on illusory displacement suggest that perceived position is not based solely on a fixed retinotopic mapping. Either the

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☆ Portions of these results were presented at the Vision Sciences Society, Sarasota, FL, May 2003.

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doi:10.1016/j.visres.2005.05.029

local mapping of receptive fields is flexible, as is the case for eye movements (Duhamel, Colby, & Goldberg, 1992) or there may be another level of representation for location, one that is vulnerable to both motion and eye movement signals.

In spite of a growing field of research on this topic, the role of attention in the position distortion phenomenon has yet to be fully explored. There has been converging evidence from different fields of study that shifts of attention are tightly coupled with eye movements. In psychophysical studies, prior allocation of attention to the position of the saccade target is required for making accurate saccades (Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995). Khurana and Kowler's (1987) study of concurrent smooth pursuit and visual search suggested that smooth eye movements and perception share the same attentional mechanism. These psychophysical results were supported by studies from neurophysiology and functional neuroimaging showing that eye movements and shifts of attention are controlled by the same or a largely shared neural system (for neurophysiology: Kustov & Robinson, 1996; Moore, Armstrong, & Fallah, 2003; Moore & Fallah, 2001, 2004; for neuroimaging: Corbetta et al., 1998; Culham et al., 1998). Given this close relationship between eye movements and attention, it is possible that the position shifts seen at the time of the eye movements could be caused by the attentional shifts that accompany the eye movements rather than by oculomotor components themselves.

Attention has also been proposed as a key mechanism for high-level motion processes. Several authors distinguish a low-level motion system operating on local, velocity-based motion detectors from a high-level motion system that tracks the changing positions of target features or objects and may require attention to do so (Anstis, 1980; Braddick, 1980; Cavanagh, 1992; Cavanagh & Mather, 1989; Julesz, 1971; Lu & Sperling, 1995). Typically, both low- and high-level motion systems respond to an ordinary moving target so the effects of motion in many of the previous studies of position shifts may arise from either motion system or from both.

A few studies have attempted to isolate the contributions of high-level motion to the position distortion effect (Shim & Cavanagh, 2004; Watanabe, Sato, & Shimojo, 2003; Watanabe, Nijhawan, & Shimojo, 2002). In our laboratory, for example, we (Shim & Cavanagh, 2004) have tested position shifts caused by the apparent motion seen in a bistable-quartet. This stimulus has four dots located at the corners of a square, two dots are presented in each frame, top left and bottom right, for example, alternating with top right and bottom left. While the subject views the display, the path of the motion is sometimes vertical (up and down motion seen on the left and right vertical paths) and sometimes horizontal (left and right motion on the top and bottom). This bistable display allowed us to test the influence of the perceived direction of motion on position shifts without changing the spatio-temporal properties of the display. We placed brief flashes adjacent to either the vertical or horizontal sides of the array and found that an illusory position shift was seen only when the test flashes were adjacent to the path where motion was perceived.

Because of the balanced locations of the dots in the quartet stimulus, low-level motion, if there was any, would have equal strength on the horizontal and vertical paths, so we attributed the position shifts to high-level, apparent motion that was seen along only one path at a time. Several authors have suggested that apparent motion results from the displacement of attention from the first location to the second (Horowitz & Treisman, 1994; Shioiri, Yamamoto, Kageyama, & Yaguchi, 2002; Verstraten, Cavanagh, & Labianca, 2000; Wertheimer, 1912) and we relied on this view to claim that the position shift was caused by attention. However, attention was not explicitly manipulated in our study.

To investigate the role of attention more directly, we employ the attentive tracking paradigm, which provides an explicit control over the locus of attention. In the tracking task we use, we are able to dissociate the trajectory of attention from the contributions of low-level motion and eye movements. First of all, we use a rotating grating (Fig. 1) so that fixation is easy to maintain, eliminating eye movement factors. Second, in the rotating grating, low-level motion energy is present continuously in all locations so that its contribution is held constant. When the subject is tracking a single pair of bars of a moving grating with attention, we then have a changing location of attention while eye movements and low-level motion are eliminated or held constant. If the perceived position of a briefly flashed test depends on the location

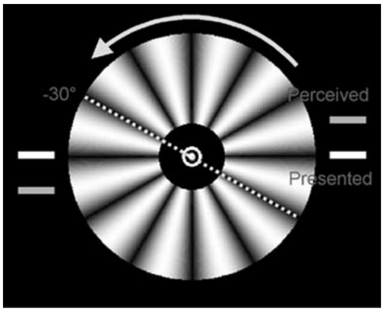

Fig. 1. An example of the stimulus configuration used in Experiment 1. The curved arrow at the top of the grating indicates the direction of the grating's rotation and the two white bars adjacent to the grating represent one of the two positions of the flashes (3 and 9 o'clock positions). The gray dashed line on the grating indicates one target bar position (−30°) among six positions in total. Dark gray bars above and below the white bars represent the perceived position of the flashes for this target position.

of attention in this display, we can then link attention directly to position distortions.

In the first experiment, a rotating sinusoidal luminance grating was used to investigate the position shift effect modulated by attentive tracking. In Experiment 2, a rotating color grating was superimposed on a luminance grating that rotated in the opposite direction. When the subject tracked bars of the color grating in one direction, the net low-level motion was strongly in the opposite direction (Cavanagh, 1992). The effects of low-level and high-level motion are then in opposite directions in this case and the relative strength of each in producing position distortions can be compared. The results from both experiments support a critical role for attention in the position distortion phenomena.

2. Experiment 1

In the first experiment, a rotating sinusoidal luminance grating was used to measure illusory displacement of stationary flashes. For each trial, while observers were attentively tracking a pair of stimulus bars (dark bars) of the rotating radial grating, briefly flashed lines were presented at different offset angles between the tracked bars and the flashes. Two flash locations (3 and 9 o'clock/6 and 12 o'clock positions) were randomly probed to prevent observers from prematurely moving attention onto a known flash location before the flashes were presented.

Observers reported whether the bottom flash was to the left or right of the top one (for tests at 6 and 12 o'clock), or right flash higher or lower than the left one (for tests at 9 and 3 o'clock). The perceived misalignment of the flashes was evaluated as a function of the relative position of the tracked bars to the flashes at the moment of the flashes. Tracking performance was confirmed at the end of each trial. Position shifts in attentive tracking were also compared with the misalignment effect when the rotating grating was passively viewed without tracking.

To control for the possible effect due to any difference in physical stimulus, the radial grating was always at an identical orientation (dark bars aligned with vertical and horizontal) for each of the tracked bar positions when the flashes were presented. This limited the locations probed for attention to offsets of integral multiples of 30°.

2.1. Methods

2.1.1. Observers

Three observers (two informed observers—one of the authors, WS and JW—and one naïve observer, LG) with normal or corrected-to-normal vision participated in the experiment.

2.1.2. Stimuli

The observers were tested with a chin rest 57 cm away from a calibrated Apple Color monitor (600×400 pixels, 67 Hz refresh) controlled by a Macintosh G4 computer. All stimuli were presented on a black background ($0.1\ \mathrm{cd/m^2}$). The fixation point was a bull's-eye with a radius of 0.63° ($50.6\ \mathrm{cd/m^2}$) displayed at the center of the screen.

The stimulus was a radial grating subtended 11.75° in diameter with a 3.13° hole at the center. The grating consisted of 12-cycle sinusoidal luminance modulation at contrast of 98.5%. A pointer ($50.6\ \mathrm{cd/m^2}$, $0.09° \times 0.8°$) was provided to indicate the target bar for attentive tracking. The test flashes ($50.6\ \mathrm{cd/m^2}$) were $0.09° \times 1.17°$, and were presented at 0.2° outside the grating.

2.1.3. Procedure

Observers attentively tracked a pair of stimulus bars (dark bars) of the rotating grating (2 Hz, 10 rpm) indicated by a pointer while fixating on the bull's-eye. The pointer rotating with the target pair was visible for 1 s. Observers continued to track the indicated bars with attention after the pointer disappeared. 1.5 s after the pointer offset, test flashes were presented for 15 ms (1 frame) randomly either at the 3 and 9 o'clock positions or at the 6 and 12 o'clock positions. Two flash locations were used to prevent a possible confound from allocation of attention to a known flash location before the flashes were presented. For example, when the grating rotated counterclockwise, the target bar at 60° ahead of the flashes at the 3 and 9 o'clock positions was located at 30° past the flashes at the 6 and 12 o'clock positions. This ambiguity was maintained for all test locations. To avoid motion aftereffects, the direction of rotation (clockwise or counterclockwise) alternated on each trial.

Observers judged whether the right flash appeared above or below the left flash or whether the bottom flash appeared to the left or the right of the top flash depending on a flash location (method of constant stimuli, two alternative forced choice task). Sixteen trials were tested for nine values of flash offset. The threshold of perceived alignment at which the observers reported the flash was offset in the direction of perceived motion at 50% was calculated with a linear interpolation procedure of the psychometric function. Four estimates (each based on 36 trials) of the psychometric function contributed to the standard errors.

The position of the tracked bars at the moment of the flashes varied by an integer number of cycles of the grating away from the flash locations. As a 12-cycle grating was used, one cycle of grating corresponded to 30°. Thus, six target locations were multiples of 30° (except 0°) covering 180° around the flash locations (−90°, −60°, −30°, 0°, 30°, and 60°). A negative sign indicates that the target bar was ahead of the location of the flashes by the corresponding degrees and a positive sign means that the target bar was past the flashes at the time of the flashes. For instance, if the tracked bar was at −90° the target pair was 90° before the flash locations when the flashes were presented.

At the moment of the flash, the radial grating was always at an identical orientation (dark bars aligned with vertical and horizontal) for each of the tracking test positions. After the response to the flashes, the observers were asked whether the bar indicated by the markers (50.6 cd/m^2, 0.2° × 0.2°) outside the grating was the bar they tracked. The marked bar was either a target bar or an adjacent (on the clockwise or the counterclockwise side) dark bar. If the observers' response was incorrect, the trial was excluded from the data analysis and an additional trial was run at the end of each block. The average rate of repeated trials was 4.9%, 5.1%, and 9.1% for observers LG, WS, and JW, respectively. The target bar locations and the flash locations were randomly intermixed within a block.

In the passive viewing condition, observers passively viewed the same stimulus without tracking for 2.5 s before the flashes were presented, which was the equivalent exposure duration for an attentive tracking condition. At the moment of the flashes, the grating was at the same orientation as in the attentive tracking condition.

2.2. Results

Since there was no significant effect of the direction of motion on the flash shift the data for clockwise and counterclockwise rotation were combined for the data analysis.

The flashes appeared shifted from their physical position at most of the target bar locations, but, more importantly, the direction and the magnitude of the shift effects were modulated by the angle between the tracked target bars and the flashes (Fig. 2). Before the tracked bars had reached the location of the flashes (−90°, −60°, and −30°), the two flashes showed a large misalignment in the direction of the grating and tracking motion, whereas once the tracked bars had past the flash locations (30°), the illusory position shifts were largely reduced or even slightly reversed. As the target bar was getting farther away (60°) from the flashes, the direction of misalignment was again in the direction of the grating's motion. The largest shift was seen when the tracked bar was in −30° test position and this corresponds to a 500 ms interval before the tracked bar and the flash position would be aligned. This optimal offset is much longer than that reported by Durant and Johnston (2004, 60 ms) but it is the shortest interval that we tested. It is possible that the illusory position shift might have reached an even higher value had we tested briefer intervals (tracked bar positions between −30° and 0°) corresponding to the optimal offset found by Durant and Johnston.

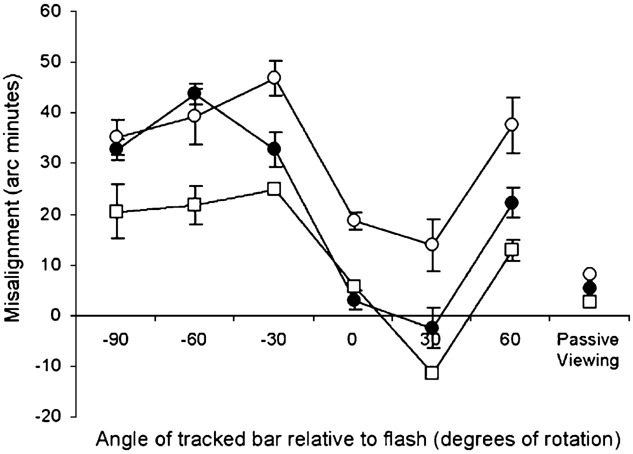

Fig. 2. Experiment 1: The size of the misalignment as a function of the angle of rotation between the test flashes and the location of the target bar at the moment of the flashes for the three observers, LG (open circle), WS (filled circle), and JW (open square). The ordinate shows the perceived misalignment of flashes in arc minutes of visual angle. Signs were arbitrarily assigned such that a positive value indicates the misalignment in the direction of the motion of the grating and a negative value indicates the misalignment in the opposite direction of motion. The abscissa shows six different test locations of a target bar in attentive tracking. The size of misalignment for a passive viewing condition is also presented on the far right for comparison. Error bars show ±1 SEM. The error bars smaller than the size of the symbols are not presented.

These results showed intriguing asymmetrical position shifts depending on the location of the attentive tracking target: a stationary flashed stimulus was pushed away ahead of the approaching tracking locus, but once tracking had moved past the flash locations, the perceived position appeared unaffected or slightly repelled by the tracked location. Because the stimulus grating was always at the same orientation for all target locations and the only difference was the location of attention at the moment of flashes, these results cannot be explained by the difference in physical stimulus. These results, therefore, clearly demonstrated the modulation in position shifts by attentive tracking.

Interestingly, similar asymmetrical position shifts were found in other studies, where a motion stimulus was viewed without attentive tracking required or a moving target was pursued by smooth eye movements. This similarity in the pattern of results for the present study and for the studies of motion (Durant & Johnston, 2004; Watanabe et al., 2003) and smooth pursuit (Van Beers et al., 2001) suggests that attention may underlie the position shifts in all these paradigms. This will be discussed in more detail later.

Note also that the magnitude of the position shift in attentive tracking (20–50 arc min) was much larger than the size of misalignment in passive viewing (5–10 arc min). Moreover, the shifts observed in the passive viewing condition of this experiment were smaller than the shifts reported in previous studies (15–20 arc min) using a similar stimulus (Durant & Johnston, 2004; Whitney & Cavanagh, 2000). One difference between our study and these previous ones was the exposure duration. In our study, the exposure duration for the rotating grating in passive viewing was set to 2.5 s to match the exposure duration of the motion stimulus in the attentive tracking condition. This is longer than the range of 0–900 ms used by Whitney and Cavanagh (2000) and 750 ms in Durant and Johnston (2004). The prolonged viewing of the motion stimulus could have caused more adaptation, which subsequently made the position shift effect smaller than in previous studies although still significant.

3. Experiment 2

In Experiment 1, since attention-based motion and low-level motion always moved in the same direction, it is not clear whether attention-based motion alone without a low-level motion signal is sufficient to produce these position shifts.

To further examine whether the effect seen in the previous experiment is attention-based, we next pitted two motion signals against each other using luminance and color gratings moving in opposite directions (Fig. 3). In this combined grating, when color and luminance contrasts are set appropriately, only the color bars are clearly visible. The luminance bars are hard to detect and difficult or impossible to track (Cavanagh, 1992). When passively viewed, however, the luminance grating's motion is dominant and sets the perceived direction. Nevertheless, as soon as one of the color bars is tracked with attention, the motion of the tracked bars is then visible as they seem to swim upstream through the opposing motion of the luminance grating. This stimulus guarantees that only high-level motion is seen in the direction of the color grating when it is attentively tracked and that the net low-level motion is in the opposite direction during tracking.

Fig. 3. The combined grating used in Experiment 2. Color and luminance gratings, rotating in opposite directions, are superimposed. While the direction of the luminance grating's motion (clockwise in this picture) is apparent when passively viewed, the direction of the color grating's motion (counterclockwise) is dominant when the color bar is tracked with attention.

3.1. Methods

3.1.1. Observers

The three observers who were tested in Experiment 1 also participated in this experiment.

3.1.2. Stimuli

Superimposed color and luminance gratings moving in opposite directions were used. A purple-green color grating moving in one direction was superimposed on a luminance grating moving in the opposite direction. The color grating was created by the modulation of purple (a mixture of red and blue phosphors) and green phosphors out of phase. The luminance grating was made in the same way but the modulations were added in phase. The CIE x and y coordinates of the phosphors were 0.284 and 0.592 for green and 0.357 and 0.189 for purple. Mean luminance was 50.3 cd/m^2 and close to white (CIE x and y: 0.339 and 0.287).

The contrast of color grating was fixed at 40% (where 100% denoted the maximum out-of-phase modulation of the phosphors) and that of the luminance grating at 10%. The relative luminance modulation of purple and green phosphors was set to approximate equiluminance for each observer using the minimum-motion criterion (Cavanagh, Anstis, & MacLeod, 1987). All other parameters of stimulus were identical to Experiment 1.

3.1.3. Procedure

In the attentive tracking condition, observers tracked a pair of stimulus bars (purple bars) of the color grating with attention. The flashes were presented varying the angle between the flashes and the location of the target bar at the moment of flashes (−90°, −60°, −30°, 0°, 30°, and 60°). If the tracking response at the end of a trial was incorrect, the trial was rerun at the end of each block. The average rate of repeated trials was 13.7%, 10.3%, and 11.8% for observers LG, WS, and JW, respectively.

In the passive viewing condition, observers passively viewed the stimuli for 2.5 s before the flashes were presented. At the moment of the flashes, the grating was at the same orientation as in the attentive tracking condition.

3.2. Results

As shown in Fig. 4, the pattern of results was almost the same as that of the previous experiment with a luminance grating alone. Even though the low-level motion was rotating in the direction opposite to that of the attention-based motion, there was strong attentional modulation of the perceived position of the flashes in the direction of the color grating's motion. Also, there was little or no significant misalignment in the direction of the luminance grating's motion in the passive viewing

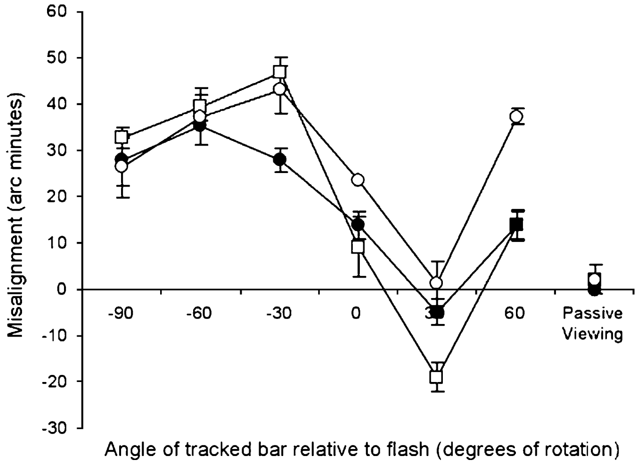

Fig. 4. Experiment 2: The size of the misalignment as a function of the angle between the test flashes and the location of the target bar at the moment of the flashes for the three observers, LG (open circle), WS (filled circle), and JW (open square). Since the color and luminance gratings were counter-rotating, positive values in misalignment indicate position shifts in the direction of the color motion and negative values indicate shifts in the direction of the luminance motion (arbitrary coding). Error bars show ±1 SEM. The error bars smaller than the size of the symbols are not presented.

condition even though the perceived direction of motion was clearly that of the luminance grating.

These results, using a superimposed grating, clearly showed that high-level, attention-based motion is sufficient on its own to produce position shifts appropriate to its direction even while low-level motion was moving in the opposite direction.

4. Discussion

The perceived position of a test adjacent flashed to an attentively tracked target is strongly modulated by the location of attention when low-level motion and eye movements are controlled. The effect was evident even when low-level motion was in the direction opposite the direction of attention displacement. These results provide important evidence that attention-based tracking processes are sufficient on their own to produce position shifts of stationary tests.

One characteristic of the results was a strong asymmetry in the size and direction of the position shifts before and after the tracked bar reached the location of the test flashes. Before the tracked bar had reached the flash locations, the flashes appeared displaced in the direction of the motion, but once the tracking locus had passed the flash locations, the misalignment was significantly reduced or even reversed.

Importantly, similar asymmetry in mislocalization was demonstrated in related studies where a motion stimulus was viewed without attentive tracking required (Durant & Johnston, 2004; Watanabe et al., 2003). For example, in Durant and Johnston's (2004) work, a single bar, instead of a grating, was rotating at the center and the flashes were presented at different offset angles between the bar and the flashes. The size of the position shift seen in the flash was maximal before the bar reached the flash location, which agrees with our results. In their stimulus, however, since it was a single bar that was moving, the physical stimulus was changing as test location changed. In our tracking task, the stimulus was identical for each test location and only the locus of attention varied. One possible explanation for the similar results observed in these studies is that the participants in the Watanabe et al. (2003) and Durant and Johnston (2004) studies may have tracked the moving bar with attention even if tracking was not explicitly required. A moving object has a powerful draw on attention, and this may explain the similar results in their studies and ours.

Durant and Johnston (2004) found that time interval before the flash was the critical factor modulating the effect rather than the spatial offset before the flash. Because we did not test different speeds we cannot differentiate between position and time factors in our study. The timing of our maximal shift (500 ms at −30° position) was much longer than the optimal temporal interval that they reported (60 ms) but we did not test any shorter (closer) delays so we cannot determine whether the optimal timing values for the two experiments would agree or not. In the absence of the appropriate speed manipulation, we cannot even determine whether the attention modulated shift shows an optimal timing as opposed to an optimal spacing. One additional difference between their study and ours is the speed of the motion stimulus. Durant and Johnston (2004) used the single bar moving at the speed of 40 rpm or higher whereas we used a grating rotating at a single, much slower speed (10 rpm). The motion-energy-based low-level motion system and the attention-based high-level motion system could differentially contribute to the position shift in these different speed ranges. At the lower speed, attentive tracking may dominate as it was shown in our study that the position shift was much smaller in the passive viewing condition compared to the attentive tracking condition. At higher speeds, however, the low-level motion mechanism could become a more powerful contributor to the position shift particularly since the ability to track positions with attention is severely limited above 8 Hz (Verstraten et al., 2000). The low-level motion system may show more time dependence for the position shift than does the high-level system, although as we mentioned above, we cannot make any statements comparing the two possibilities from our data.

Another important parallel is seen in the asymmetrical localization errors during smooth-pursuit eye movements (Mateeff & Hohnsbein, 1988; Mitrani & Dimitrov, 1982; Van Beers et al., 2001). In the study by Van Beers and colleagues (2001), when observers were pursuing a moving dot, probes presented ahead of the smooth pursuit target appeared largely displaced in the direction of the eye movements but the localization errors were much smaller for the probes behind the pursuit target. This work is particularly informative because attention-based tracking is analogous in many ways to smooth pursuit. Attentive tracking can be seen as "covert efference copy" in a manner similar to the overt efference copy of pursuit eye movements (Cavanagh, 1992).

The similar pattern of results found for attentive tracking, motion and smooth pursuit suggests that the same attention-based mechanisms may have been implicated in both. In particular, we propose that directional attentional repulsion may be the source of these position effects in the various experiments. In the original finding on attentional repulsion reported by Suzuki and Cavanagh (1997), a bar flashed near an attention cue appeared pushed away from the cue. However, their study only tested attention fixed on a static target (static attention cues), not attention tracking a moving target. The repulsion field around the focus of attention appeared to be omnidirectional when it was generated by a stationary attention cue.

We suggest that the attentional repulsion effect may change from an omnidirectional effect to a directional effect when attention is moving. In this case, the perceived location of nearby transients is more strongly repelled when approaching than when receding. A neural mechanism of attentional repulsion can be found in neurophysiological research on reshaping or remapping of receptive field associated with attention or eye movements. In V4, a strong modulation of receptive fields was shown toward a saccade target or the focus of attention (saccade: Tolias et al., 2001; attentional shifts: Conor, Preddie, Gallant, & Van Essen, 1997). Similar but larger migration of receptive fields was also observed in the lateral intra-parietal area (LIP) prior to saccadic eye movements (Duhamel et al., 1992). Such strong receptive field recruitment around the attentional focus or eye movement targets results in increased receptive field coverage at those spots and loss of coverage in the surrounding regions. This could consequently lead to visual space distortion as well as enhancement of visual processing (for a more detailed model see Suzuki & Cavanagh, 1997).

We have proposed that attention leads to a position shift because a moving attentional focus distorts the space around it. An alternative to our proposal might see the effect of attention as arising from the delay in switching from tracking the bar to assessing the flash location. The switching might then generate a position distortion. Observers do have to switch at least some of their attention from the bar to the flashes when they made the spatial judgment. However, it is unlikely that this switching can produce a spatial shift. First, the flash itself is not in motion so delays in switching to it cannot alter its sensed location in any obvious way. Second, any delay caused by attention switching would be more or less the same for the different positions of the tracked bar when the test was flashed. This should predict no effect of location of the tracked bar whereas the data reveal a strong effect of position. On the other hand, we might imagine the time to switch from the tracked bar to the test could be influenced by the distance between the tracked bar and the flash and maybe some cost of switching direction when the tracked bar is beyond the test. Whatever the case, we are unable to arrange these factors to create the direction of effects we observed. We can also ask whether the spatial judgment required a significant switch of attention away from the tracked bar. Observers needed to maintain some attention on the tracked bar even after the flash was presented as the accuracy of tracking was assessed at the end of the trial. Although it is possible that they quickly switch the focus of attention from the flash back to the bar to perform the tracking task it was often the case that observers lost the tracked bar if they entirely switched their attention to the flash. Trials with errors in tracking were eliminated from analysis (6.4% in Experiment 1 and 11.9% in Experiment 2 on average). It would be more likely that attention is briefly divided for the two tasks, the spatial judgment of the flashes and the attentive tracking of the bars, rather than entirely switched over to the flashes. Therefore, it would be reasonable to assume that the effect is not due to attention switching because, first, there is no obvious mechanism for switching to produce a shift, and second, even if there were such a mechanism, switching would not produce the observed pattern of results. Finally, we screened trials for tracking errors to remove those where complete switching might have produced.

Is there also a contribution to position distortions from low-level motion? Low-level motion signals accompanied the position shifts not necessarily because they played an independent role per se but because they accompanied the motions of the target bar in Experiment 1. In Experiment 2, however, tracking of the color grating was in the direction opposite to the motion of the superimposed luminance grating. The low-level motion was dominated by the luminance grating and yet the position shift was in the opposite direction, consistent with the direction of tracking of the color grating.[1] This shows that the low-level motion is not necessary for the position shift. Similarly, our previous work utilizing

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[1] The effect we found for passive viewing in Experiment 1 disappeared in Experiment 2. However, since the color grating in the second experiment moved in the opposite direction of the luminance grating, it is possible that observers inadvertently followed color bars from time to time, canceling any passive effect.

ambiguous motion stimuli (Shim & Cavanagh, 2004) also demonstrated sufficiency of high-level, attention-based motion on its own in producing position shifts without low-level motion. However, this does not indicate that there is no independent contribution from low-level motion. Although our experiments were not designed to demonstrate an independent contribution of low-level motion, the results are not inconsistent with a low-level contribution. In contrast, the experiments demonstrate a strong, independent contribution from the displacement of attention.

In conclusion, the study presented here shows that attentive tracking of a moving stimulus can alter the perceived position of a briefly presented stationary object independently of low-level motion and eye movements. Based on the close relationship between the effects of moving attention, motion and eye movements on position judgments, we suggest that attention may be a common factor mechanism underlying several position distortions.

Acknowledgments

This work was supported by Grant EY09258 from the National Eye Institute to Patrick Cavanagh and Graduate Fellowship from the Kwanjeong Educational Foundation awarded to Won Mok Shim.

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