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# The Role of Perception in the Mislocalization of the Final Position of a Moving Target

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The judged final position of a moving stimulus has been suggested to be shifted in the direction of motion because of mental extrapolation (representational momentum). However, a perceptual explanation is possible: The eyes overshoot the final position of the target, and because of a foveal bias, the judged position is shifted in the direction of motion. To test this hypothesis, the authors replicated previous studies, but instead of having participants indicate where the target vanished, the authors probed participants' perceptual focus by presenting probe stimuli close to the vanishing point. Identification of probes in the direction of target motion was more accurate immediately after target offset than it was with a delay. Another experiment demonstrated that judgments of the final position of a moving target are affected by whether the eyes maintain fixation or follow the target. The results are more consistent with a perceptual explanation than with a memory account.

Physical principles operating in the outside world seem to be incorporated into the mental system and determine how the environment is represented in memory (see Hubbard, 1995b, for an overview). For example, when an observer is asked to judge the final position of a moving target, the remembered position is often displaced in the direction of the anticipated future motion of the target. Analogous to the physical momentum of real-world objects, the mental representation of a moving stimulus cannot be halted instantaneously. Instead, it continues for some time such that the judged final position is ahead of the actual position (e.g., Freyd & Finke, 1984; Hubbard & Bharucha, 1988). In the present series of experiments, we show that this localization error may not result exclusively from a process operating in memory but from perceptual processes as well. According to our hypothesis, the control of eye movements and a foveal localization bias substantially contribute to the displacement.

Freyd and Finke (1984, 1985) presented observers with a series of images of a rectangle that was rotated by different degrees about its center. The orientation of the rectangle was changed by 17° with each successive presentation so that the rectangle appeared to rotate. Freyd and Finke (1985) presented the rectangle three times for 250 ms each with blank interstimulus intervals of 100 ms to 900 ms. Thus, the object did not undergo smooth, apparent motion, but its motion was only implied in the sequence of pictures. After the presentation of the inducing stimuli, a fourth rectangle appeared that was rotated either slightly further in the direction of motion than the last stimulus of the inducing sequence or opposite to the implied direction of motion. The observers' task was to decide whether the fourth rectangle was in the same position as the third test stimulus. Test rectangles oriented slightly past the final orientation were more likely to be accepted as being in the same orientation as the final rectangle. Freyd and Finke's explanation of these effects was that the implied motion of the object is mentally extrapolated and cannot be instantaneously stopped at the time the target vanishes. In analogy to the physical momentum of real-world objects, Freyd and colleagues referred to the inertia associated with mental representations of motion as *representational momentum.* Consistent with this interpretation, the observed shift in memory increased with velocity (Freyd & Finke, 1985; Finke, Freyd, & Shyi, 1986), suggesting that the same principles apply to physical and mental momentum.

Extending the findings of Freyd and colleagues, Hubbard demonstrated that mental representations of the final position of a moving target may be influenced by physical principles other than momentum. He observed effects of context and expectation (see Hubbard, 1995b, for an overview), and he referred to the broader class of spatial memory distortions that are produced by environmentally invariant or other noninvariant factors as *memory displacement.* Hubbard used displays depicting the apparent motion of a linearly moving target (e.g., Hubbard, 1990, 1994, 1995a; Hubbard & Bharucha, 1988); that is, the motion of the object was not implied but was smoothly rendered. Instead of the same–different procedure used by Freyd and colleagues, Hubbard had

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observers judge the location where they thought the target had vanished by positioning a cursor. These judgments allowed for the evaluation of displacements not only in the direction of motion but also in the direction orthogonal to the direction of motion. With this method, evidence for mental analogues of gravity (Hubbard, 1990; Hubbard & Bharucha, 1988), friction (Hubbard, 1995a), and weight (Hubbard, 1997) was obtained. For instance, when observers were asked to position the cursor on the vanishing point (VP) of a horizontally moving target, they showed a tendency to shift the remembered position downward as well as in the direction of motion. For vertically moving targets, the forward shift was smaller when the target moved up than when it moved down (Hubbard & Bharucha, 1988). This outcome supports the idea that momentum and gravity were incorporated into the mental representation of the moving object's final position. Further, it was observed that expectations about the future direction of the motion influence memory displacement (Hubbard, 1994; Hubbard & Bharucha, 1988; Verfaillie & D'Ydewalle, 1991). For instance, in an experiment (Hubbard & Bharucha, 1988) in which observers repeatedly saw a target reversing its direction at a visual barrier, memory displacement at the reversal point was not in the current direction of motion (through the barrier) but in the anticipated direction of motion (away from the barrier). This situation suggests that the path of the mental extrapolation may be modulated by expectations about the future path of the target. Finke and Freyd (1989) metaphorically described the situation as a train going down a track in a switchyard. Setting a switch determines the track that the train might follow, but the train would still have to go some way. Thus, the direction in which the train's physical momentum is expressed depends on the setting of the switch. Similarly, representational momentum may be influenced by expectations.

The interpretation of the mislocalization of the final target position or orientation provided in these earlier studies was always in terms of a distortion occurring in memory. Presumably, mental extrapolation shifted the representation of the object's position into the anticipated direction of motion. Thus, the process accounting for the distortion was assumed to be localized at a postperceptual, cognitive stage. Implicitly, it was assumed that the raw sensory information accurately represented the physical world. In fact, a number of studies attempted to rule out the possibility that low-level, sensory factors account for memory displacement (see *Discussion* of Experiment 1; Finke & Freyd, 1985; Finke et al., 1986; Finke & Shyi, 1988; Hubbard & Bharucha, 1988).

However, the rather minor role assigned to perception may be inappropriate given that moving objects were depicted. In everyday life, observers track moving objects that are of interest to them rather actively. For instance, a spectator in a tennis match actively follows the trajectory of the ball with her eyes. It is most unlikely that she will fixate a point on the horizon to be passively stimulated. Among others, Gibson (e.g., 1966, 1979) pointed out that the sense organs should not be considered passive receptors but rather as part of active perceptual systems. He distinguished between obtained and imposed stimulation (e.g., Gibson, 1966, pp. 31–33). In his view, imposed stimulation resulted from the passive stimulation of the receptor organ, which is similar to taking a picture with a camera. In contrast, obtained refers to the active acquisition of stimulation by orienting the receptor organ toward a location of interest. Active perception occurs in perception–action loops that involve stimulation of the receptor organ and redirecting of the organ in a circular fashion. As for the visual system, at least three ways of orienting the receptor organ can be distinguished. First, focal perception may be covertly oriented by a shift of attention; second, the eyes may be redirected; and third, the head (or the whole body) may be moved. It is important to note that the notion of active perception leaves room for higher level processes. Where perception is directed is to a large degree under voluntary control and may therefore be guided by expectations (Gibson, 1966, p. 280). Thus, similar to memory displacement, active perception may be influenced by higher level cognitive processes.

The notion of active perception can be easily applied to the experiments of Hubbard and colleagues. In a typical study, the target moved at moderate velocity (e.g., 4.2°/s–17.7°/s in Hubbard, 1990; 5.4°/s–34.8°/s in Hubbard & Bharucha, 1988) across a part of the screen (an average distance of approximately 10°). The velocities and durations of stimulus motion were mostly adequate for smooth pursuit eye movements (see Meyer, Lasker, & Robinson, 1985; Robinson, 1965). Because observers were instructed to indicate the last-seen position of the target, it is plausible that they tried to visually track the target. This hypothesis cannot be ruled out because in the experiments of Hubbard and Bharucha (1988), no instructions concerning eye movements were given, observers' eye movements were not monitored, and no fixation dot was provided. If observers did track the target by one or the other kind of eye movement, the location of the perceptual focus had to be continuously updated because the target was in motion. The eyes had to be shifted very briefly after reaching a particular location so as not to lose track of the target. Consequently, the observer had to plan where to direct the eyes or attention next as soon as a particular target location had been reached. This type of behavior comes very close to what Gibson called *obtained* stimulation because it involves alternating perception and action (reorienting).

Our speculations about the perceptual behavior of an observer in one of Hubbard's experiments leads to a straightforward prediction about what might occur when the target vanishes at any given position along its trajectory: Because the observer has to continuously update the position of her eyes to follow the target, a reorientation of the perceptual apparatus in the direction of motion may occur during or after the sudden disappearance of the target. Thus, the observer is likely to overshoot the final location of the target, and the position of the eyes (or attention) will be displaced from the actual VP in the direction of motion. Consistent with this hypothesis, it has been shown that the eye drifts in the direction of target motion after smooth pursuit of a target that vanishes at a random point on a linear trajectory (Mitrani & Dimitrov, 1978).

Further, we hypothesize that the state of the perceptual system shortly after the disappearance of the target influences localization of the final position. For static stimuli, it has been demonstrated that stimuli presented in the periphery are localized closer toward the fovea than they actually are (*foveal bias;* e.g., Mateeff & Gourevich, 1983; Müsseler, Van der Heijden, Mahmud, Deubel, & Ertsey, 1999; O'Regan, 1984; Osaka, 1977; Van der Heijden, Müsseler, & Bridgeman, 1999). In other words, localization of a peripheral target depends on the retinal eccentricity of the target. The same may also apply to dynamic stimuli. When a moving target suddenly disappears, the eye overshoots the final position of the stimulus, such that the fovea is shifted in the direction of motion. Subsequently, the foveal bias may cause the final position of the target to be localized in the direction of the fovea's motion (i.e., in the direction of the target's motion; see also Figure 1). On the basis of these assumptions, one may derive the somewhat paradoxical prediction that localization performance should be better when the observer is not moving the eyes than when the observer is tracking the target to keep it in the fovea; that is, judged target position should be more accurate when the target is presented peripherally in a retinal region of inferior acuity than when it is kept in the region of highest acuity (the fovea).

In Experiment 1, we used stimuli that closely resemble those of Hubbard and Bharucha (1988) to test the hypothesis that the perceptual focus of the observer overshoots the final position of the target. In Experiment 2, we showed that expectations about the future path of a target influence perceptual behavior. Finally, in Experiment 3 we showed that the mislocalization error is largely reduced when the eyes are still.

## Experiment 1:
## Identification and a Horizontally Moving Target

The purpose of the first experiment was to examine whether observers' perceptual focus moves beyond the final position of a

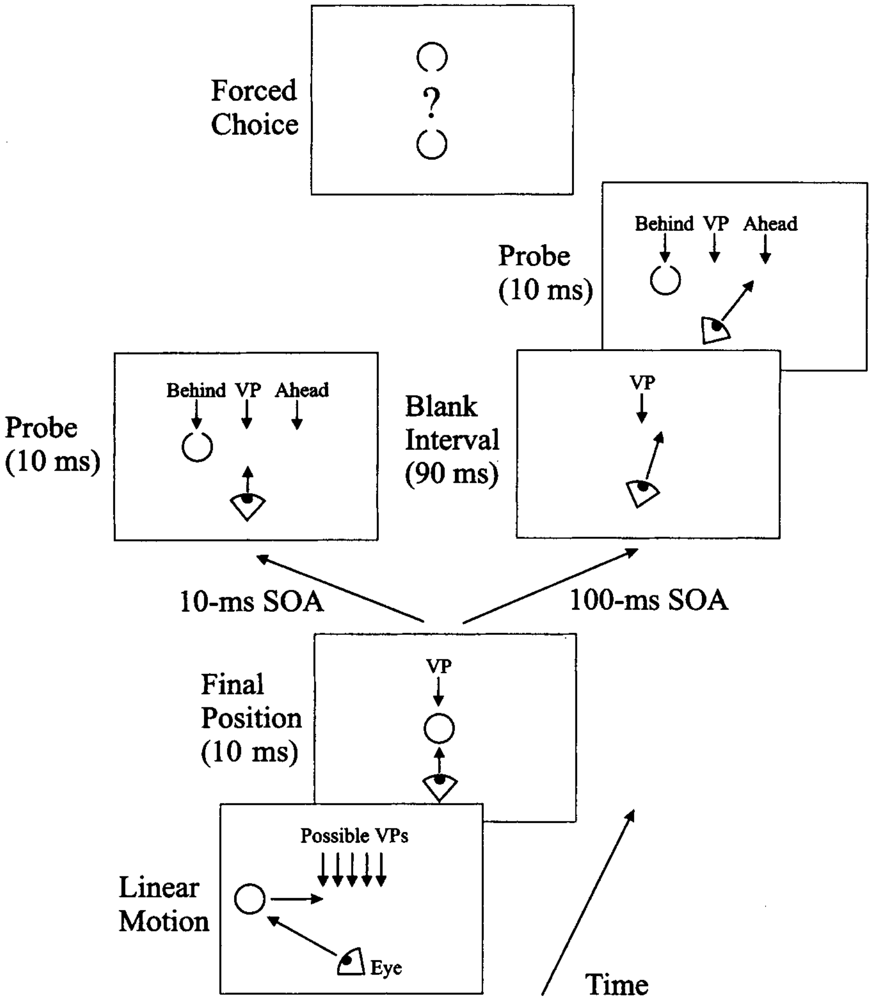

*Figure 1.* Sequence of events in Experiment 1. A target moved linearly from left to right (or right to left) and disappeared unpredictably at one of five possible vanishing points (VPs). A probe stimulus was presented with a stimulus onset asynchrony (SOA) of 10 ms or 100 ms to the last target presentation. It appeared some distance from the VP either in the direction of motion (ahead) or opposite the direction of motion (behind). Note that only with an SOA of 100 ms was there a blank interval of 90 ms between final target presentation and probe presentation. Then, participants had to indicate whether the probe stimulus had a gap on the top or on the bottom. To make the judgment, they selected one of two circles appearing on the screen that were similar to the two possible probe stimuli but stayed on the screen until a choice was made. Observers were asked to track the target with their eyes. After the target disappeared, the eyes are expected to move into the direction of motion after target offset (overtracking), that is, the eyes are directed at a position ahead of the target. Thus, probes presented ahead should be more accurately identified with an SOA of 100 ms because they are closer to the fovea, the region with the highest visual acuity. With a 10-ms SOA, this is not the case; probes ahead and behind are equally distant from the fovea.

moving target. To this end, we used stimuli similar to those used in Hubbard and Bharucha's (1988) Experiment 1 but changed the nature of the task. As an indicator of where observers were looking after target offset, we used an identification task. Observers were asked to indicate whether an unfilled circle that served as a probe stimulus had a gap on top or on bottom. Performance in this identification task was highly dependent on where on the retina the probe was presented. When the probe appeared in the fovea, judgments were highly accurate. However, the more peripheral the probe position, the more errors were made because of the decreasing retinal acuity in the periphery. The probe stimulus was presented some distance from the VP either in the direction of motion (ahead; see Figure 1) or in the opposite direction (behind) and was shown either immediately after the target had vanished or with a delay. No difference in identification rates between the two probe positions was expected immediately after target offset. As observers were instructed to track the target with their eyes, the eye should still be approximately at the final target location immediately after target offset, such that probes ahead and behind are equally likely to be accurately identified. However, as the eyes are expected to overshoot the final position of the target, observers should look at positions further in the direction of motion some time after target disappearance. Consequently, probe stimuli presented ahead should be closer to the fovea and probes presented behind should be more peripheral. Thus, some time after target offset higher identification rates are expected in the ahead condition because small differences between the two possible probe stimuli (i.e., where the gap was) are more likely to be identified. Further, moving attention to a location ahead of the final stimulus position (Van Donkelaar, 1999) may also lead to superior identification of probes presented ahead.

## Method

*Participants.* Eight students at the Ludwig-Maximilians University of Munich were paid for their participation. All reported normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

*Apparatus.* The stimuli were created using a Matrox Millenium II graphics card (Matrox, Dorval, Quebec, Canada) controlled by a personal computer. The display had a resolution of 1280(H) × 1024(V) pixels on a 21-inch (diagonal) screen. The refresh rate was 96 Hz.

*Stimuli.* To avoid asymmetries arising from the different horizontal and vertical screen dimensions, we presented stimuli on a square display window centered on the screen. The display window completely filled the screen vertically but only partially horizontally to compensate for the different screen dimensions. The window had an approximate size of 32° × 32° (1,024 × 1,024 pixel) and was white. The remaining parts of the screen were rendered black. The target was an unfilled black circle with a diameter of 0.8°. The target entered from one edge of the display window and moved linearly toward the opposite side. It disappeared unpredictably at one of five possible VPs that were 2.5° apart and centered around the midpoint of the display window. The target position was updated on each screen refresh, yielding the impression of smooth motion. Probe stimuli were similar to the target stimuli except that a 0.1° white gap was inserted either on the top or bottom of the circle. The gap was at the horizontal midpoint of the circle. The probe stimulus was presented for 10 ms.

*Design.* A four-factor within-participants design was used. The first factor was the velocity of the target, which varied randomly among 5.8, 17.4, and 34.8°/s. The second factor was the position of the probe stimulus. The probe appeared either 1° from the VP in the direction of motion or in the direction opposite to the direction of motion. The former location will be referred to as ahead, the latter as behind the VP. The third factor was the stimulus onset asynchrony (SOA) between the last presentation of the target and the onset of the probe, which was approximately 10 ms (i.e., the last target stimulus and the probe were presented in successive frames) or 100 ms (i.e., a separation of 10 frames). The 12 combinations of target velocity, probe position, and SOA were fully crossed with two directions of motion (left or right), five possible VPs, and two possible probe types (gap on top or bottom) for a total of 240 trials.

*Procedure.* Participants sat in a dimly lit room approximately 50 cm from the screen. Head movements were restricted by a chin rest, and viewing was binocular with no restrictions concerning eye movements. Observers received 15 practice trials drawn randomly from the 240 experimental trials. A trial was initiated by pressing a key on the computer keyboard. Then, the target appeared and moved until it vanished and the probe stimulus was presented. 500 ms after the probe disappeared, two unfilled circles with gaps on bottom and top similar to the probe stimuli appeared. They were positioned above and below the screen center and stayed on the screen until the participant responded. For half of the participants, the circle with the gap on top was above the screen center during the judgment task, and the circle with the gap on the bottom was below. For the other half, the relative position was reversed. Observers' task was to select the circle with a gap corresponding to the probe stimulus that had been presented by clicking on the circle with the mouse. Feedback was provided after each trial.

## Results

Mean proportions correct (PC) are graphed in Figure 2. Mean individual performance ranged between .63 and .78 PC. A three-way analysis of variance (ANOVA; Velocity × Probe Position × SOA) was conducted on arcsin-transformed PC. A significant interaction between SOA and probe position emerged, $F(1, 7) = 15.22$, $MSE = 0.054$, $p < .0059$. To adjust the significance level for usage of multiple $t$ tests, we used a Bonferroni correction for $p < .05$ throughout. The $t$ tests showed no significant difference between probes presented ahead and behind the VP with an SOA of 10 ms (0.67 vs. 0.66 PC); however, performance at the two locations differed significantly with a 100-ms SOA (0.8 vs. 0.64 PC, $p < .025$). When the probe was presented ahead of the VP, accuracy was higher than when it appeared behind, $F(1, 7) = 10.69$, $MSE = 0.1$, $p < .0137$; PCs were 0.73 and 0.65, respec-

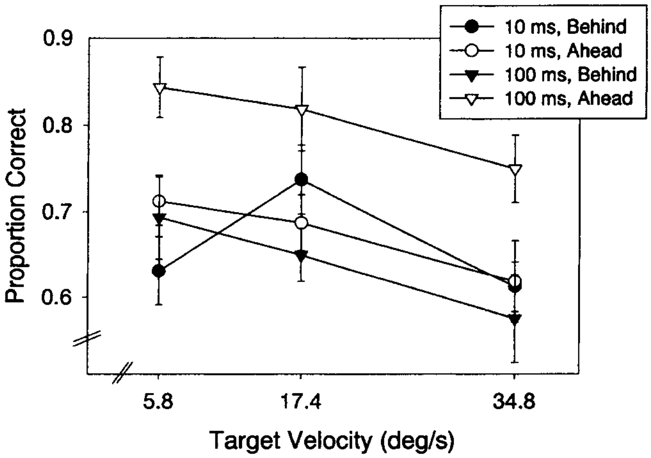

*Figure 2.* Mean proportion correct and standard errors (between participants) as a function of target velocity, position of probe (ahead or behind), and stimulus onset asynchrony in Experiment 1. deg = degrees.

tively. Accuracy decreased from 0.72 PC at the lowest velocity to 0.63 PC at the highest velocity, $F(2, 14) = 7.30$, $MSE = 0.5$, $p < .0067$. Accuracy was higher with the long SOA than with the short SOA (0.77 vs. 0.66 PC), $F(1, 7) = 6.50$, $MSE = 0.08$, $p < .0381$. No other effect approached significance ($p > .1$).

### *Discussion*

The pattern of identification performance supports our assumption that observers' perceptual focus moved beyond the final position of the target. Identification performance was unaffected by probe location at the short SOA, indicating the perceptual focus to have been near to, if not identical with, the final target position. Identification performance was affected, however, by probe location at the late SOA in that it was significantly better at the ahead location. Again, such a pattern indicates that the perceptual focus shifted in the direction of target motion after the disappearance of the target.

One cannot account for this effect with appeals to oculomotor planning that may have occurred during the 90-ms interval passing between the short and long SOAs, for the minimal time required to initiate an eye movement is roughly 200 ms (e.g., Rayner, Slowiaczek, Clifton, & Bertera, 1983). Also, the brief presentation of the stimulus (10 ms) prevented eye movements from occurring toward the stimulus during its presentation. Even if the image of the probe may have persisted for longer than 10 ms (see Coltheart, 1980, on visible persistence), its position on the retina did not change during this interval. Thus, the forward perceptual shift seems to have been brought about by the execution of an eye movement that had been planned prior to the offset of the stimulus. This interpretation receives further support from the inverse relationship between target velocity and identification rates. That is, as target velocity increased and thus required faster oculomotor pursuit, the distance covered by the eyes on target offset is expected to increase (see Mitrani, Dimitrov, Yakimoff, & Mateeff, 1979). This situation may have resulted in the probe being presented at more and more peripheral retinal eccentricities, which, in turn, may have resulted in decreased identification rates.

Moreover, the lack of an effect of probe position at the short SOA renders an account in terms of forward masking (i.e., a degrading influence of a mask on the perception of subsequently presented stimuli) unlikely. One may argue that forward masking at locations opposite the direction of motion made identification in the behind condition more difficult. If this had been the case, then performance in conditions with a short SOA should have been worse for probes presented behind compared with probes presented ahead. This was clearly not the case.

## Experiment 2: Identification and a Bouncing Target

In Experiment 2, we sought to determine whether a variable that captures the status of the perceptual system reflects the displacement pattern observed with a target that changes its direction at predictable locations (see Figure 3). According to our hypothesis, the observer is actively adjusting the position of her eyes to keep track of the target. This process is largely under voluntary control and therefore open to the influence of expectation. Thus, it is predicted that expectation should influence low-level sensory factors by guiding perceptual adjustments. Predictive eye movements that anticipate directional changes of a pursued target because of prior experience (Boman & Hotson, 1992; Dodge, Travis, & Fox, 1930; Kowler, 1989) or cues indicating the path of motion (Kowler, 1989) are cases in point. Predictive smooth pursuit movements drive the fovea off a moving target when an abrupt change in the direction of target motion is expected. Functionally, predictive eye movements facilitate resynchronization of target and eye velocity after the change in direction of motion has taken place. However, shortly before and during the change of direction, the deviation of eye and target position is increased.

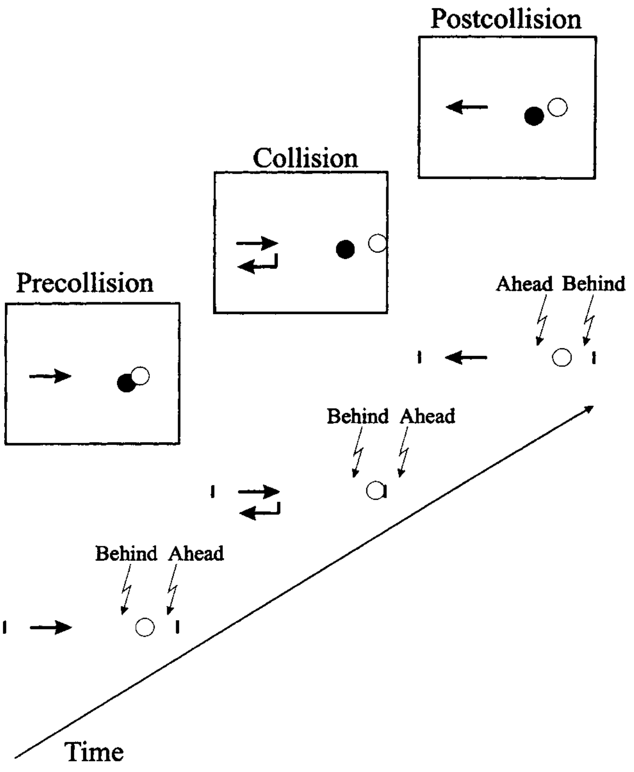

*Figure 3.* Stimulus displays similar to those used by Hubbard and Bharucha (1988) are depicted in the upper panel, and those used in Experiment 2 are shown in the lower panel. In both studies, the target bounced between two delimiters and disappeared either before the VP (precollision), at the delimiter (collision), or after having made contact with the delimiter (postcollision). In the upper panel, the actual vanishing point (VP) is indicated by an unfilled circle, and the judged VP is indicated by a filled circle. Displacement was opposite the direction of motion in the precollision and collision conditions, indicating anticipation of the future path. In the postcollision condition, the standard forward shift was observed.

One may argue that the presumed role of expectation renders our perceptual account of the mislocalization error inconsistent. Expectation may be considered to depend on memory of past events. Thus, it may appear that our argument against the influence of memory-related factors in mislocalization loses force because we refer to memory-related stages. We agree that there is no principled difference between the assumed role of expectation in memory displacement and in our perceptual account. In both cases, expectation is supposed to modulate the processes responsible for the mislocalization. However, there is a fundamental difference in what the two positions assume expectation to modulate: In memory-related accounts, expectation is assumed to modulate the automatic extrapolation of future target positions (Finke & Freyd, 1989) or may even cause the shift itself (T. L. Hubbard, personal communication, January 31, 2000). In our perceptual account, however, we assume that expectation modulates control of the perceptual focus, and the control of this focus results in mislocalization.

To test the hypothesis that expectation guides perceptual processes, we used stimuli similar to Hubbard and Bharucha's (1988; Experiment 4). Hubbard and Bharucha studied localization of a target that appeared to bounce between two walls. The target approached the inner surface of a frame, made contact with it and then moved in the opposite direction. The target would bounce off the frame from one to five times before target and frame vanished simultaneously. When the target disappeared after having touched the wall, a forward shift in remembered position was observed. This finding is consistent with prior research showing that the last presentation of a linearly moving object is displaced in the direction of motion. In contrast, when the target vanished before or at the time it made contact with the wall, the localization error was not in the direction of motion but was opposite to it. Thus, displacement did not follow the actual direction of motion but followed the anticipated direction of motion.

In the present study, we probed observers' perceptual focus using the same procedure as in Experiment 1. A probe stimulus appeared either ahead or behind the VP of the target and observers' task was to indicate whether the probe stimulus had a gap on top or on bottom. If the higher identification rate in the probe-ahead condition of Experiment 1 was due to low-level factors, such as physical momentum of the eyes, then performance should improve in the ahead condition regardless of the future path of the target. In contrast, if the planning of eye movements was the reason for the improved identification in the probe-ahead-condition (see the results of Boman & Hotson, 1992), then identification performance should follow roughly the same pattern as that manifested in the localization judgments reported in Hubbard and Bharucha's Experiment 4. In the pre- and postcollision conditions, an advantage should be obtained in the ahead condition. If the target vanishes at the point of impact, this advantage should be smaller or even reversed; that is, performance should be better in the behind condition.

## *Method*

*Participants.* Eight students at the Ludwig-Maximilians University of Munich were paid for their participation. All reported normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

*Apparatus and stimuli.* Apparatus and stimuli were as in Experiment 1 with the following exceptions: A single velocity of 14.4°/s was used. In addition to the target, two small black 0.03° × 0.19° lines were drawn 6.4° to the left and right of the screen center at the vertical midpoint of the screen (see Figure 3). The frame that delimited the trajectory of the target was chosen to be less salient than Hubbard and Bharucha's frame to avoid masking. The target moved horizontally within the frame and reversed its direction at the delimiting markers. The target approached the markers between one and five times, appearing to bounce off the delimiters.

*Design.* The first factor was the VP of the target. The target could disappear either 1.7° before the target reached the marker (precollision) at the moment of impact with the marker (collision) or 1.7° after the target reached the marker (postcollision). The second factor was the position of the probe. It could either appear 1° ahead of the VP of the target or 1° behind the target's VP. Note, if the probe appeared ahead in the collision condition, its location was outside the delimited path; in all other conditions the probe appeared inside. The third factor was the SOA between the last target presentation and the appearance of the probe (10 and 100 ms). The 12 combinations of VP, probe position, and SOA were fully crossed with two starting locations of the target (left or right collision point), probe type (gap on top or bottom), and five reversals of direction (bounces) for a total of 240 different trials.

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

## *Results*

Mean PCs are graphed in Figure 4. Mean individual performance ranged between .62 and .82 PC. A three-way ANOVA (VP × Probe Position × SOA) on arcsin-transformed PC yielded a triple interaction between VP, probe position, and SOA, $F(2, 14) = 16.48$, $MSE = 0.06$, $p < .0002$. Significant interactions between probe position and SOA, $F(1, 7) = 6.84$, $MSE = 0.09$, $p < .0346$, and VP and probe position emerged, $F(2, 14) = 18.17$, $MSE = 0.06$, $p < .0001$. There was a main effect of SOA, $F(1, 7) = 10.91$, $MSE = 0.07$, $p < .0107$, showing that responses were more accurate with the long SOA than with the short SOA (0.72 vs. 0.78 PC).

In a second three-way ANOVA, we collapsed the data from the pre- and postcollision condition as the anticipated and the current direction of motion coincided in these conditions. A significant interaction between VP and probe position, $F(1, 7) = 21.67$, $MSE = 0.07$, $p < .0023$, and a triple interaction between VP, probe position, and SOA was obtained, $F(1, 7) = 17.37$, $MSE = 0.05$,

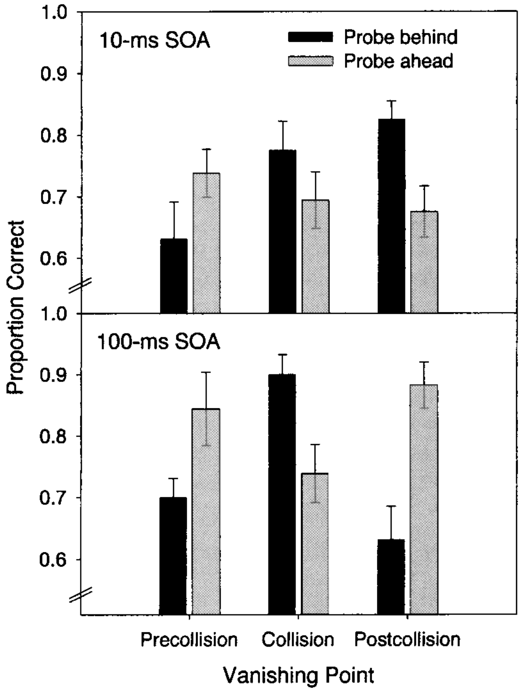

*Figure 4.* Mean proportion correct and standard errors (between participants) as a function of vanishing point, position of probe (ahead or behind), and stimulus onset asynchrony (SOA) in Experiment 2. Conditions with a 10-ms SOA are presented in the upper panel, and conditions with a 100-ms SOA are presented in the lower panel.

$p < .0042$. Using *t* tests, the two probe locations were compared for each combination of SOA (10 ms vs. 100 ms) and VP (collision vs. pre-/postcollision). With the 10-ms SOA, no significant differences emerged. With the 100-ms SOA, performance was better for probes placed ahead than behind in the pre-/postcollision condition (0.67 vs. 0.86 PC, $p < .0125$). In the collision condition, there was a trend in the opposite direction; probes presented behind tended to be more accurately identified than probes presented ahead (0.9 vs. 0.74 PC, $p < .02$).

### *Discussion*

The pattern of identification performance in the collision and postcollision conditions with a 100-ms SOA mirrors the pattern of displacement found by Hubbard and Bharucha (1988). In their study, the displacement was opposite the direction of motion in the collision condition and in the direction of motion in the postcollision condition. Similarly, identification performance was better with ahead target placement in the postcollision condition, whereas the opposite was true in the collision condition. In the precollision condition, the patterns deviate, however. Hubbard and Bharucha found negative displacement in this condition that was smaller than in the collision condition; by contrast, we found identification performance to be worse for probes presented behind the target's vanishing point. Both patterns of results reflect some sort of expectancy about the future position of the target: Either the path between precollision VP and turning point is anticipated, or the path following the reversal of direction is anticipated. We suspect that the different task demands may have induced these short- or long-term expectancies. In our experiments, feedback was given after each trial, which should have motivated observers to optimize their identification performance. This task-demand, which was not present in Hubbard and Bharucha's paradigm, may have induced our observers to engage in finer-scale oculomotor tracking, thus producing better identification in the precollision condition for probes presented ahead of target position. In Hubbard and Bharucha's experiments, no feedback was provided, and, consequently, there was less motivation to engage in the fine-scale oculomotor control demanded by our paradigm.

More important than this difference in the precollision condition is that the pattern of identification performance suggests that the future path of the target influenced observers' pursuit eye movements. The identification performance at an SOA of 100 ms reflects where observers were planning to direct their gaze at the time the target vanished: When the target disappeared before or after the collision, identifying a probe presented ahead of the target's VP was easier. In contrast, when the target vanished at the point of collision, identification was better opposite to the direction of motion. This result suggests that observers' smooth-pursuit patterns were not based simply on extrapolations of the target's immediate direction but rather on anticipations regarding the target's future direction. Thus, we have again demonstrated that the state of the visual system after the disappearance of the target closely corresponds to the pattern of displacement reported previously.

## Experiment 3: Position Judgment and Fixation Versus Pursuit Movements

To further test our hypothesis that the point of fixation after stimulus offset is crucial for the judged displacement, we directly compared localization of the final position in two different eye movement conditions. In one, observers were instructed to actively follow the target. We expected that fixation would be shifted in the direction of motion after stimulus offset because of oculomotor overshoot (Mitrani & Dimitrov, 1978), and in this pursuit condition, we expected a replication of the results obtained by Hubbard and Bharucha (1988). In the other condition, we asked observers to fixate a point slightly below the trajectory of the target. Because no pursuit eye movements and no subsequent overshoot was expected to occur in this condition, we expected the forward localization error to be largely eliminated here. Further, because fixation was below the trajectory, the downward shift was expected to increase because of the foveal bias. To ensure that the test was as direct as possible, in the present experiment we used the same dependent measure as used by Hubbard and Bharucha (1988), namely, localization by mouse pointing.

### *Method*

*Participants.* Seven observers from the Max Planck Institute for Psychological Research and the Ludwig-Maximilians University of Munich who had considerable experience with laboratory tasks involving the control of eye movements were paid for their participation. All reported normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

*Apparatus and stimuli.* Apparatus and stimuli were the same as in Experiment 1 with the following exceptions: The target was a filled circle of the same size as in Experiment 1 (0.8°). A fixation dot (0.03°) was presented at the horizontal center of the screen, 2° below the trajectory of the target (the vertical center). The fixation dot was visible throughout the experiment. The spacing of the VPs was reduced to 1.5°. A cross-hair cursor equal in size to the target was used. It always appeared at the screen center.

*Monitoring of eye movements.* The horizontal position of the left eye was monitored with a head-mounted, infrared, light-reflecting eyetracker (IRIS Model 6500, Skalar Medical B. V., Delft, the Netherlands). The analog signal was bandpass, demodulated, and low-pass filtered (DC 100 Hz, 3 dB). The experimenter controlled the eye position on an LCD display and rejected trials in which the observer erroneously pursued or fixated. These cases were rare (2% of all trials). If an eye-movement error occurred, the experimenter pressed a key, and feedback about the error was given. The trial was repeated in the remainder of the block. Head movements were restricted by a chin rest.

*Design.* The first factor was eye-movement control. Participants either had to fixate a centrally located stimulus during target presentation or track the target by smooth pursuit eye movements. Eye-movement control was blocked. Four participants started with the fixation condition, the remaining 3 with the pursuit condition. The second factor was the velocity of the target (12.5°/s and 20.3°/s). The third factor was the VP of the target relative to the screen center. There were five levels of VP, +/−3°, +/−1.5°, and 0°. Positive numbers indicated that the target disappeared to the right of the screen center, and negative numbers indicated VPs to the left of the screen center. The two velocities, two directions of motion, and five VPs were fully crossed, yielding 20 distinctive trials. Each condition was repeated once in six successive blocks within each of the two eye-movement blocks for a total of 240 trials.

*Procedure.* Each trial was initiated by pressing a button. After 750 ms, the target appeared and moved along its trajectory. Then, 500 ms after the target disappeared, a cross-hair cursor appeared at the center of the screen. Participants were instructed to position the cursor as exactly as possible on the position where they thought the target vanished and to confirm the position by a click of the left mouse button. No feedback was provided.

### *Results*

The deviation of the adjusted cursor position from the actual VP was determined. The deviation along the axis of motion (horizontal) is referred to as *M displacement,* and the deviation along the orthogonal (vertical) axis is referred to as *O displacement.* M displacement in the direction of motion received a positive sign, M displacement in the opposite direction a negative sign. O displacement received a negative sign when the cursor was positioned lower than the actual VP and positive when the position was higher. As a measure of the absolute error, we calculated the Euclidean distance of the judged VP from the actual VP. Mean M and O displacements and absolute errors are graphed in Figures 5 and 6.

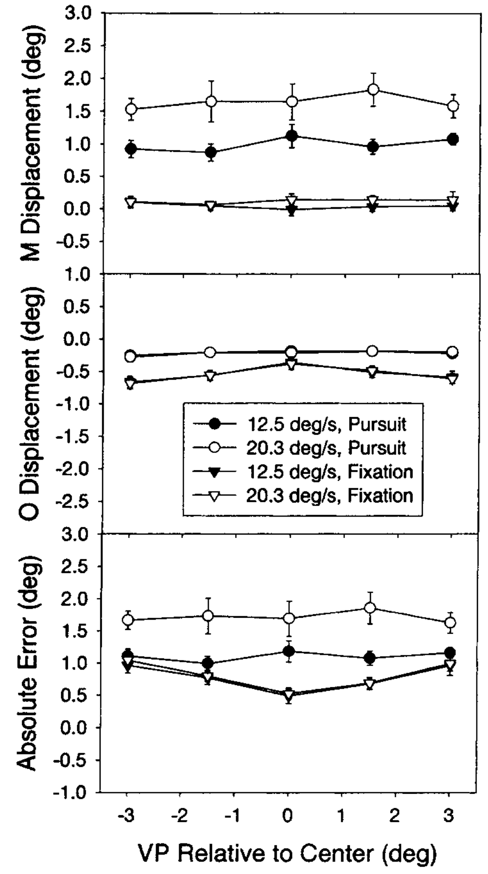

*Figure 5.* The upper panel shows mean M displacement, the middle panel shows mean O displacement, and the lower panel shows mean absolute error as a function of target velocity, vanishing point (VP) relative to center, and eye movement condition in Experiment 3. A negative sign of the VP relative to center indicates that the target vanished on the left side of the screen; a positive sign indicates that it vanished on the right side. Error bars indicate standard errors (between participants). deg = degrees.

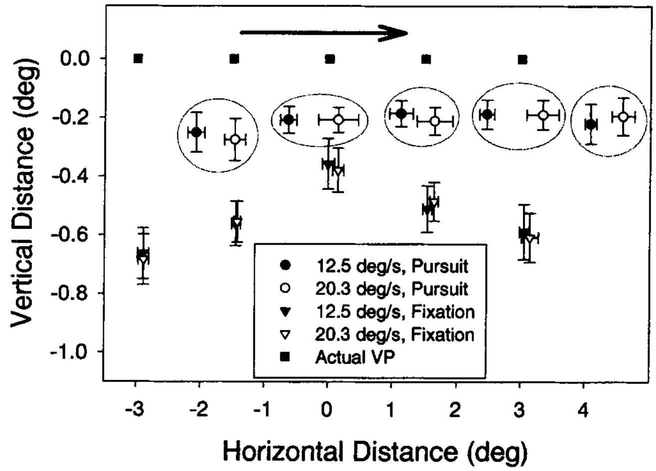

*Figure 6.* Judged vanishing point (VP) as a function of target velocity, eye movement condition, and VP in a two-dimensional scatter plot. Horizontal and vertical distance is given relative to the screen center. The judged VPs were collapsed across direction of motion and are graphed for a target moving from left to right. Note the difference in scale between vertical and horizontal distance. A negative vertical distance indicates a location lower than the center of the screen, and a positive vertical distance indicates a location higher than the center. For the horizontal dimension, negative values indicate a location on the left side of the screen, and positive values indicate a location on the right side. For each combination of eye movement and target velocity, the data are ordered according to the actual VP; for instance, the leftmost data point in each group represents the mean for the leftmost actual VP. In the pursuit condition, ellipses indicate the grouping according to actual VP. Error bars indicate the mean standard error (between subjects). deg = degrees.

*M displacement.* A three-way ANOVA (Eye Movement × Velocity × VP) was performed on M displacement. There was a significant triple interaction between eye movement, velocity, and VP, $F(4, 24) = 3.61$, $MSE = 0.017$, $p < .0193$. The interaction between eye movement and velocity reached significance, $F(1, 6) = 28.12$, $MSE = 0.1$ $p < .0018$. Larger M displacement occurred with pursuit eye movements than with fixation (1.32° vs. 0.08°), $F(1, 6) = 36.31$, $MSE = 1.47$, $p < .0009$. M displacement increased with velocity (0.52° vs. 0.88°), $F(1, 6) = 35.37$, $MSE = 0.13$, $p < .001$.

To further evaluate differences between the eye movement conditions, we ran two separate ANOVAs (Velocity × VP) for each eye movement condition. In the pursuit eye movement condition, M displacement increased with speed (0.98° vs. 1.64°), $F(1, 6) = 36.87$, $MSE = 0.2$, $p < .0009$, and an interaction between velocity and VP was confirmed, $F(4, 24) = 3.38$, $MSE = 0.027$, $p < .025$. In the eye fixation condition, no significant effects emerged ($ps > .12$). Importantly, velocity did not have an effect on M displacement, $F(1, 6) = 3.09$, $p < .1291$. M displacement was 0.04° in the slow and 0.12° in the fast condition. Overall, M displacement was significantly different from zero in the pursuit condition (1.31°, $p < .025$) but not in the fixation condition (0.08°, $p > .2$).

*O displacement.* A three-way ANOVA (Eye Movement × Velocity × VP) was performed on O displacements. There was a significant interaction between eye movement and VP, $F(4, 24) =$

15.62, $MSE = 0.004$, $p < .0001$. O displacement was more negative with fixation than with pursuit (−0.54° vs. −0.21°), $F(1, 6) = 21.66$, $MSE = 0.17$, $p < .0035$. Further, an effect of VP emerged, $F(4, 24) = 11.79$, $MSE = 0.01$, $p < .0001$.

To evaluate the interaction between eye movement and VP, we ran separate one-way ANOVAs for each eye movement condition. With pursuit eye movements, the effect of VP was not significant ($p > .11$). With fixation, the effect of VP was significant, $F(4, 24) = 18.94$, $MSE = 0.01$, $p < .0001$, indicating that O displacement decreased with eccentricity. Overall, O displacement was significantly different from zero in both the fixation and the pursuit condition ($ps < .025$).

*Absolute error.* A three-way ANOVA (Eye Movement × Velocity × VP) was run on the Euclidean distance between judged and actual VP. There was a significant three-way interaction, $F(4, 24) = 4.39$, $MSE = 0.01$, $p < .0083$. The interaction between velocity and eye movement reached significance, $F(1, 7) = 30.22$, $MSE = 0.095$, $p < .0015$, indicating that absolute error increased significantly with speed when pursuit eye movements were performed (1.10° vs. 1.71°, $p < .025$) but not with fixation (0.77° vs. 0.81°, $p > .1$). Further, a significant interaction between eye movement and vanishing point emerged, $F(4, 24) = 6.16$, $MSE = 0.062$, $p < .0015$. Absolute error increased with velocity (0.94° vs. 1.26°), $F(1, 6) = 39.39$, $MSE = 0.09$, $p < .0008$. Importantly, absolute error was smaller with fixation than with pursuit (0.79° vs. 1.41°), $F(1, 6) = 9.87$, $MSE = 1.35$, $p < .02$.

To further evaluate differences between the eye movement conditions, we ran two separate ANOVAs (Velocity × VP) for each eye movement condition. With pursuit eye movements, velocity interacted with VP, $F(4, 24) = 3.45$, $MSE = 0.02$, $p < .0231$, indicating that the difference between the two velocities was somewhat smaller at the center VP. With the high velocity, the absolute error was larger than with the low velocity, $F(1, 6) = 36.14$, $MSE = 0.18$, $p < .001$. The effect of VP was not significant ($p > .9$). With fixation, the effect of VP was significant, $F(4, 24) = 9.48$, $MSE = 0.06$, $p < .0001$, indicating that the absolute error increased with eccentricity. No other effect reached significance.

### *Discussion*

The present results show large effects of eye movement type on localization performance. We discuss effects on M displacement and O displacement in turn. First, there was a clear reduction in the size of the forward shift when the eyes were not following the target. In fact, M displacement was close to zero in this condition, whereas it reached a size comparable to previous studies in the pursuit condition. In the 20°/s condition, we found M displacement to be 1.64°, which is in line with Hubbard and Bharucha (1988, estimated from Figure 1), who reported 1.51° with 17.4°/s, and Mitrani et al. (1979, estimated from Table 1), who found 1.7° with 19.2°/s. In the 12.3°/s condition, we found a forward shift of 0.98°, which is slightly less than in Hubbard (1990, estimated from Figure 1), who found 1.3° with a velocity of 12.5°/s. The reduction of the forward shift with fixation is surprising given that the perceived velocity of a moving stimulus is higher when it is viewed with stationary eyes compared with when it is pursued by the eyes, a distortion known as Aubert-Fleischl phenomenon (Aubert, 1886; Von Fleischl, 1882; Freeman & Banks, 1998). Because the forward shift usually increases with increases in velocity (e.g., Hubbard & Bharucha, 1988), a postperceptual account would predict larger M displacement in the fixation condition because of the Aubert-Fleischl phenomenon. However, the opposite of this pattern was found.

Second, the effect of velocity on M displacement disappeared in the fixation condition. It is hard to see how an explanation of mislocalization in terms of a mental extrapolation process can explain these data. If there were a mental analogue of momentum, and the forward shift was exclusively due to this postperceptual process, then the forward shift and the effect of velocity should be unaffected by where the observer is fixating. In contrast, the absence of M displacement and velocity effects without pursuit eye movements is fully consistent with our interpretation in terms of perceptual processes. Whereas the eyes overshoot the final target position in the pursuit condition (Mitrani & Dimitrov, 1978), and this overshoot increases with velocity (Mitrani et al., 1979), this is not the case when the eyes are motionless. Thus, the tendency to localize the target closer to the fovea (e.g., Mateeff & Gourevich, 1983; Müsseler et al., 1999; O'Regan, 1984; Osaka, 1977; Van der Heijden, Müsseler, et al., 1999) produced a forward shift in the pursuit condition but not in the fixation condition.

The effects of eye movement condition on O displacement are also hard to reconcile with a postperceptual account. First, we found the judged final position to be lower than the actual VP. This finding accords with previous research reporting negative O displacement (e.g., Hubbard, 1990; Hubbard & Bharucha, 1988). This effect has been attributed to a mental analogue of gravity (e.g., Freyd, Pantzer, & Cheng, 1988; Hubbard, 1990); that is, observers have internalized a physical constraint that modifies their memory of a real-world event.

Second, we found O displacement to be more negative (i.e., the judged VP was further down) with fixation than with smooth pursuit. Again, it is hard to see how a memory-related explanation can deal with this finding. In contrast, these effects are fully consistent with prior research on the localization of peripherally presented targets. Fixation was below the target's VP, such that localization was expected to be shifted downward, that is, toward the fovea. We found the underestimation to be 13% of the Euclidean distance between fixation and VP. This proportion is well in the range of the underestimation reported previously (10%, Van der Heijden, Müsseler, et al., 1999). In the pursuit condition, the target's retinal image is more or less foveal (e.g., Engel, Anderson, & Soechting, 1999) so that a downward shift is expected to be smaller. Because a downward shift has also been demonstrated with static pictures (Freyd, 1983; Freyd et al., 1988), it may well be that negative O-displacement in the pursuit condition is attributable to mental analogues of gravity. However, the present research offers an alternative explanation of these effects. In studies investigating localization in the vertical dimension, it may have been that fixation was shifted slightly downward, thereby accounting for the supposed gravity effect. To our knowledge, no attempts have been made to clarify this issue. Given the size of gravity effects (<0.5°), however, such effects may be prevented by the limited resolution of eye tracking devices.

Further, we found M and O displacement to be affected by where the target disappeared. These effects need further clarification. We suspect that the asymmetries are attributable to differences in relative (retinal) location of the VPs with respect to the fixation point or cursor position. Cursor position and fixation point may have been used as references for location judgments, resulting in landmark attraction or memory averaging (e.g., Hubbard & Ruppel, 1999). Inspection of Figures 5 and 6 shows that judgments for the centrally located VP most often deviated from those of the other VPs, perhaps because of the cursor appearing at this position. However, the exact nature of these biases is not known. Another factor of potential importance was the eccentricity of the targets. In the fixation condition, VPs offset by +/−3°, +/−2°, and 0° from the center of the screen were 3.6°, 2.5°, and 2° from the fixation point, respectively. As the eccentricity of stimuli in the periphery is underestimated by a certain proportion, more eccentric VPs may have produced more displacement.

To defend the concept of memory distortion, two objections may be raised against our conclusions. First, one may argue that localization performance deteriorated with fixation, such that noise in the data masked the forward shift. However, our data show quite clearly that the absolute error was smaller with fixation, suggesting that performance was superior with peripheral target presentation. Second, one may argue that landmark effects account for the results. It has been shown that forward displacement is larger for objects moving toward a large stationary object than for objects moving away from it (Hubbard & Ruppel, 1999). In our experiments, the fixation dot may have acted as a landmark. However, because the fixation dot was visible with pursuit and fixation, it is unclear how the downward shift may be explained by landmark effects.

Also, the results show that expectation modulated perceptual processes that produce the forward shift and is not responsible for the effect itself. In the present experiment, observers' expectations about the future path of the target were unaffected by eye movement condition. In both the pursuit and fixation conditions, we presented exactly the same stimulus displays so that no difference in expectation about the target's trajectory should have been induced. Thus, expectation fails to account for the differences between the two conditions. We suggest that the role of expectation is to guide perception, and mislocalization results as a consequence of where the perceptual focus has been shifted.

To sum up, the results of Experiment 3 support a perceptual explanation in terms of eye movements and foveal bias. With fixation, M displacement was almost eliminated and did not change as a function of velocity. Negative O displacement, on the other hand, was more pronounced with eye fixation. These results are hard to reconcile with a postperceptual, cognitive account of mislocalization error.

## General Discussion

The present series of experiments provides evidence for the view that the mislocalization of the final position of a moving target in the direction of motion is at least partially accounted for by perceptual factors. We suggest that the observer actively tracks the target such that the eyes overshoot the final target position. Therefore, fixation is shifted in the direction of motion briefly after target offset. Because of a foveal bias, judged final position is subsequently displaced in the direction of motion. In Experiment 1, we showed that identification performance was improved at a location slightly ahead of where the target had vanished, indicating that the perceptual focus overshoots the final target position. In Experiment 2, we demonstrated that the overshoot is influenced by expectations about the future trajectory of the target. That is, we ruled out the possibility that the overshoot was simply due to low-level inertial properties of the eyes. Rather, expectancies about the future path influenced the location of the perceptual focus. In Experiment 3, we tested the contribution of eye position to displacement effects by introducing a fixation (i.e., nonpursuit) condition. We found displacement to be significantly affected by the eye movement condition. With fixation, the mislocalization in the direction of motion was reduced, whereas the shift downward (toward fixation) was increased. The results suggest that the foveal bias and eye movements contribute substantially to the localization error.

In this study, we demonstrated that perceptual factors play a role in the mislocalization of a smoothly moving target. One may wonder whether these findings generalize from apparent motion to the implied motion used by Freyd and colleagues. There are two main differences between the experiments of Hubbard (e.g., Hubbard & Bharucha, 1988) and Freyd (e.g., Freyd & Finke, 1984; Finke et al., 1986). First, Hubbard used apparent (i.e., smoothly rendered) motion of a single target on a linear trajectory. In contrast, Freyd and colleagues presented a few frames of complex stimuli that only implied the motion of the target. Second, in Hubbard's experiments, there was uncertainty about when the target disappears. The length of the target's trajectory was unpredictable. In Freyd's experiments, the positions of the target stimulus were perfectly predictable because the number of inducing displays was fixed. For instance, in Finke et al. (1986) three displays showing three dots that were displaced in different directions from frame to frame were presented. Then, the test display appeared. It appears that the conditions in the experiments of Hubbard favor the occurrence of eye movements much more than do Freyd's. When observers have to follow a linearly moving target that vanishes at some point along its trajectory, it seems almost unavoidable that the eye overshoots the final position of the target. This is not the case in experiments using Freyd's implied motion paradigm in which the final position of the target is fixed.

However, our argument that the observers actively adjust their perception to deal with upcoming stimulation patterns applies here as well. When watching a fixed number of displays showing the motion of a target stimulus, the observer expects the stimulus to move to some particular position after each presentation. The tendency to extrapolate future positions to optimally direct perceptual resources at these positions may not end at the point where the target is presented for the last time. Thus, it may well be that even when the stimulus conditions do not promote oculomotor overshoot, fixation may still be shifted in the direction of motion. However, such an interpretation appears hard to test given the size of the localization error usually observed under these conditions. For linear motion, Finke et al. (1986) noted memory shifts of 0.017°, 0.063°, and 0.09° for velocities of 0.2°/s, 0.6°/s, and 1.0°/s. It may be very difficult to devise methods to measure attentional shifts or eye movements of this size.

The present series of experiments suggests that the perceptual anticipation of future target positions contributes to the mislocalization of the final position in the direction of motion. Recently, a similar mechanism has been suggested to solve the problem of transmission time of motion information from retina to higher visual areas of the brain: To adequately perceive the location of a moving object, the brain has to compensate for this delay. It has been suggested that it does so by anticipating the future positions of the moving object (Berry, Brivanlou, Jordan, & Meister, 1999; Khurana & Nijhawan, 1995; Nijhawan, 1994; but see Whitney & Murakami, 1998; and Purushothaman, Patel, Bedell, & Ogmen, 1998, for rejoinders). For instance, a rotating line segment and another segment that is briefly illuminated when the two are aligned do not appear aligned; rather, the briefly presented segment is perceived to lag behind the rotating line (Nijhawan, 1994; for an early variant of this phenomenon, see Hazelhoff & Wiersma, 1924; Metzger, 1932). Presumably, the visual system corrects for the delay caused by the transmission from retina to cortex by anticipating or extrapolating future positions of the rotating segment. Thus, at any point in time, the perceived position is slightly ahead of the actual position. Importantly, this effect is perceptual and not memory related.

A related perceived mislocalization even occurs at the beginning of a movement. When observers are asked to determine where a fast-moving stimulus enters a window, they typically do not localize the stimulus at the edge but at some later position within that window (Fröhlich effect, Aschersleben & Müsseler, 1999; Müsseler & Aschersleben, 1998). Müsseler and Aschersleben (1998) developed an attentional account for this phenomenon assuming that the effect emerged from a displacement at the end of an exogenously triggered visual focus shift. In any case, there is growing evidence that attentional mechanisms and eye movements are closely linked (for a recent overview, see Van der Heijden, 1992, chap. 4.7–4.8; cf. also the *premotor theory of attention* by Rizzolatti, Riggio, Dascola, & Umiltà, 1987; Umiltà, Riggio, Dascola, & Rizzolatti, 1991). Thus, the present idea to relate these kinds of mislocalizations to perceptual factors associated with oculomotor control is in line with several accounts.

Collectively, these action-coupled, anticipatory phenomenal effects are consistent with a growing body of data that indicate perception and action-planning to be, to some extent, one and the same (Jordan, 1998, 1999a, 1999b; Müsseler, 1999; Prinz, 1997). Though such an approach may appear inconsistent with traditional intention/perception distinctions (Pylyshyn, 1999), it is in line with the Gibsonian notion of prospective control (Turvey, 1992) and may serve as a means of integrating the seemingly incompatible cognitive and ecological approaches to perception and action.

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