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The locus of “memory displacement” is at least partially perceptual: Effects of velocity, expectation, friction, memory averaging, and weight

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When observers are asked to localize the final position of a moving target, the judged position is usually displaced from the actual position. It has been suggested that mental processes derived from a number of invariant and noninvariant principles produce the mislocalization in memory. In this study, the effects of velocity, expectation, friction, memory averaging, and weight were reconsidered, and evidence was accumulated that supports the alternative view that the distortions arise to a large degree at a perceptual level. Effects of velocity and expectation were present when observers still perceived a persisting image of the target. It is suggested that the active reorienting of the perceptual organs explains the distortions. Furthermoremore, distortions of the perceived center of a visible stimulus may explain effects that have previously been attributed to memory averaging and mental analogues of weight. Thus, the locus of memory displacement is at least partially perceptual.

When observers are asked to judge the final position of a moving target, the remembered position of the moving target is shifted in the direction of motion. Early accounts of this error in localization drew upon a parallel between the physical momentum of the target and the momentum of the representational system (e.g., Freyd, 1987; Freyd & Finke, 1984). Since later reports showed that shifts of the final position occur in directions other than the direction of motion, the notion of representational momentum was extended in several ways (for an overview, see Hubbard, 1995b). First, it was observed that physical principles other than momentum have been incorporated into the representational system. The judged final position was shifted slightly downward, indicating mental analogues of gravity (e.g., Hubbard & Bharucha, 1988), and the downward shift increased with target size, suggesting a mental analogue of weight (Hubbard, 1997). Furthermore, when a target appeared to slide along a surface, the forward shift was reduced, which provided evidence for representational friction (Hubbard, 1995a, 1998). Second, in addition to environmentally invariant physical principles, effects of noninvariant factors were observed. Knowledge about the future trajectory (Hubbard & Bharucha, 1988; Verfaillie & D’Ydewalle, 1991) and the real-world motion of the target objects (Reed & Vinson, 1996) was shown to influence the forward shift. It is important to note that the distortion of the final position was thought to occur in memory as a result of mental processes that reflect the influence of mental analogues of momentum, gravity, friction, weight, and expectation. The distortion of the final position associated with these factors was referred to as *memory displacement* (e.g., Hubbard, 1995b).

Lately, a perceptual explanation of the basic forward shift has been suggested. Kerzel, Jordan, and Müsseler (2001) suggested that the forward shift may be due to overshooting eye movements. In a typical experiment by Hubbard (e.g., Hubbard & Bharucha, 1988), smooth linear target motion was presented. Observers either were given no instructions concerning eye movements or were asked to watch the target. Since smooth stimulus motion is an effective stimulus for the initiation of smooth pursuit eye movements (Yasui & Young, 1975), it is likely that the observers in Hubbard’s experiments pursued the target with their eyes. Because pursuit eye movements cannot be stopped instantaneously, the eyes overshoot the final target position when the target disappears at a random point along its trajectory (Mitrani & Dimitrov, 1978), so that the final fixation is shifted beyond the final target position—that is, fixation is shifted in the direction of motion. Given that peripheral targets are localized toward the fovea (e.g., Van der Heijden, Van der Geest, De Leeuw, Krikke, & Müsseler, 1999), a forward shift of the final target position results. Consistent with this interpretation, the forward bias was completely eliminated when fixation had to be maintained (Kerzel, 2000; Kerzel et al., 2001).

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In another study, the time course of the localization error was examined (Kerzel, 2000; see Freyd & Johnson, 1987, for a similar study using implied motion). It was demonstrated that the forward shift increased with time for about 250 msec after physical target offset. That is, the larger the retention interval after target offset, the larger the displacement in the direction of motion. Furthermore, the experiments showed that for 50–60 msec after target offset, observers perceived the target to be still present (Kerzel, 2000)—that is, some low-level afteractivity in the visual system persisted for some time after visual target offset (see Coltheart, 1980, for an overview). Because the eyes move in the direction of target motion for some time after target disappearance (Mitrani & Dimitrov, 1978), the target was actually seen at a position ahead of its physical vanishing point (VP) during the initial interval of 60 msec. This finding suggests that the locus of the forward shift is not high-level memory that encompasses analogues of physical principles and expectation, but—at least partially—low-level ultra-short-term visual memory. Thus, in addition to the foveal bias, the initial displacement (about 20% of the total displacement) may be accounted for by visible persistence of the target.

The question addressed in this paper is whether phenomena other than the forward shift do in fact arise at the suggested high-level processing stage. In particular, effects of velocity, expectation, friction, memory averaging, and size are reconsidered, and evidence for an explanation of these effects in terms of visible persistence and perceptual organization is provided. The basic argument underlying the experiments is the following. If localization errors of a visible target are obtained that are similar to those obtained when participants recall the position of a target, the localization error may not be interpreted as an exclusive product of memory processes. Necessarily, memory takes the content of perception as input. Thus, if the perceived position is distorted, the remembered position should be similarly distorted, even if recall is perfectly accurate.

However, memory-related magnification or reduction of the distortion may take place during the retention interval. That is, the size of the error may increase or decrease while the perceptual input is stored in visual short-term memory. It may be impossible to distinguish magnification/reduction of the perceptual distortion from an alternative account that attributes differences between perceptual and memory distortions to mental representations of physical forces and expectations. That is, an increase or decrease of the error after a retention interval may be due to internalized physical regularities or expectations that act on the (already distorted) perceptual information. However, it may be very difficult to decide whether simple magnification/reduction or the operation of some other principles accounts for different sizes of perceptual and memory errors. In sum, if a distortion is identified at a perceptual level, the identification of the exact nature of the subsequent distortions requires further study. In contrast, it would be safe to reject the hypothesis that the distortion is exclusively attributable to memory-related processes. Rather, one would have to conclude that the origin of the distortion is partially or completely perceptual.

EXPERIMENT 1
Velocity

The purpose of the first experiment was to examine the effects of velocity on the forward shift of the final position briefly after target offset. A robust finding has been that the deviation of the judged final position from the actual final position increases with increases in target velocity (e.g., Freyd & Finke, 1985; Hubbard & Bharucha, 1988; Mitrani, Dimitrov, Yakimoff, & Mateeff, 1979). Effects of velocity are consistent with the notion of representational momentum, since it takes longer for fast objects to come to a halt than it does slow objects. However, if the forward shift observed with smooth linear motion was due to overshooting eye movements that carry the persisting image in the direction of motion (Kerzel, 2000; Kerzel et al., 2001), effects of target velocity should be observed during an interval in which observers still *perceive* the target. Since the visible persistence of the target was measured to be about 50–60 msec (Kerzel, 2000), effects of velocity on judgments of the final position that occur very briefly after target offset would indicate that the locus of velocity effects is at least partially perceptual. In other words, if effects of velocity occur while observers still see the target, the distortion cannot be due exclusively to processes in memory.

To estimate the perceived position of the final physical target presentation, probe stimuli were presented around the VP of the target. Probe stimuli were presented slightly above the target stimulus, either in the direction of motion or opposite the direction of motion (see Figure 1). The observers' task was to judge whether they saw the probe to the left or the right of the target position. Left–right judgments were used to calculate the subjective VP of the target either at the physically last target presentation or 23 msec after the last presentation.

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. In the following experiments, stimuli were created by using either an ATI or a Matrox Millenium graphics card, with refresh rates of 86 and 96 Hz, respectively. The display had a resolution of 1,280 (H) × 1,024 (V) pixels on a 21-in. (diagonal) screen. The stimuli were presented on a square display window centered on the screen. The display window completely filled the screen vertically, but only partially horizontally. The window had an approximate size of 32° × 32° (1,024 × 1,024 pixels) and was white; the remaining parts of the screen were rendered black.

The target was a black disk with a diameter of 0.5°. Black on white stimulus displays were used for compatibility with the methods of Hubbard (e.g., Hubbard & Bharucha, 1988) and Kerzel (Kerzel, 2000; Kerzel et al., 2001). The target entered at one edge of the display

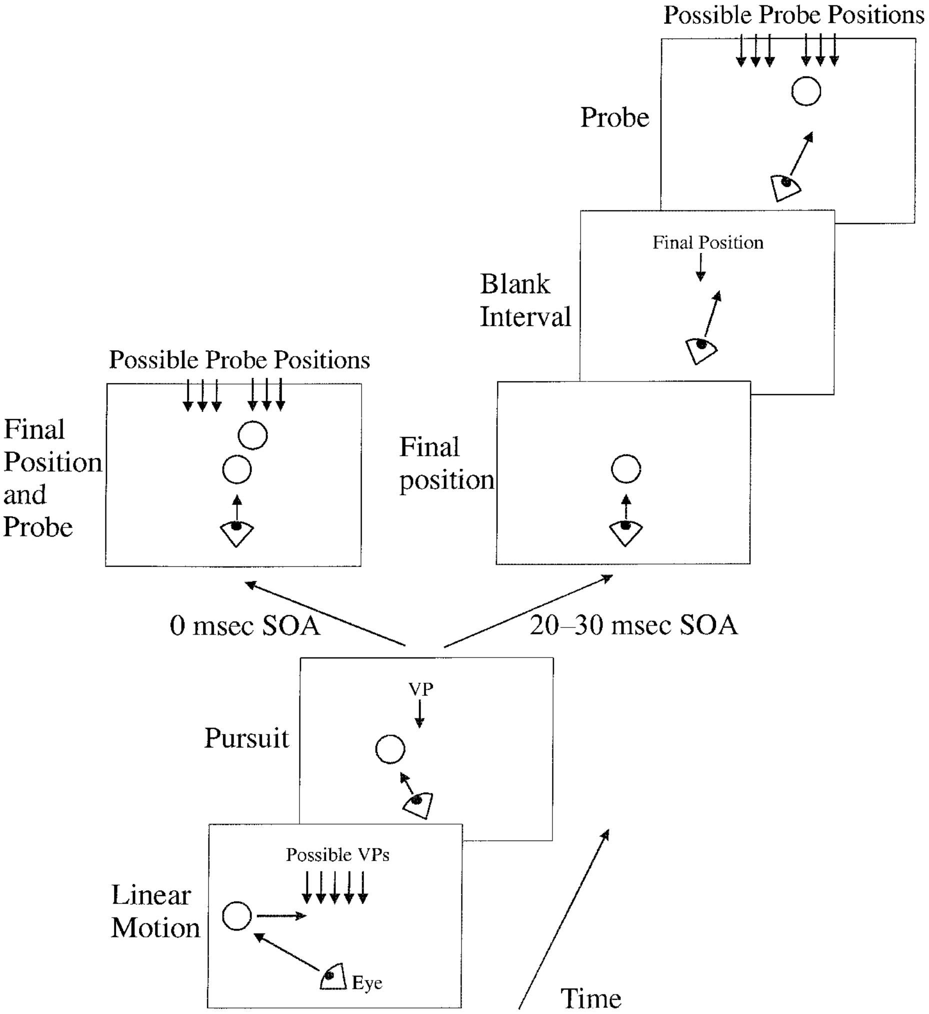

Figure 1. Schematic drawing of the sequence of events in Experiments 1–3. A target moved linearly on a horizontal trajectory. Observers were instructed to pursue the target with their eyes. At an unpredictable point along the trajectory, the target vanished. With a 0-msec stimulus onset asynchrony (SOA), the probe was presented simultaneously with the last target presentation. It appeared slightly above the target and was displaced toward the left or the right with respect to the final target position. The observers had to indicate whether the probe was to the left or to the right of the final target position. With a 20- to 30-msec interval between target and probe onset, there was a short blank interval. During this interval, the eyes continued to move in the direction of motion and carried the persisting image of the target in the direction of motion. In the example drawing, the observer may have correctly responded *right* to the probe presented with a 0-msec SOA (left panel) and erroneously responded *left* with a 20–30 msec SOA (right panel).

window and moved toward the opposite side. It disappeared randomly 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.

The probe stimulus was identical to the target stimulus and was presented 0.7° (center to center) above the target stimulus for one screen refresh (i.e., 10.4 and 11.6 msec for refresh rates of 96 and 85 Hz). The stimulus onset asynchrony (SOA) between the last presentation of the target and the onset of the probe was varied by presenting the probe stimulus in the same screen refresh cycle as the last stimulus presentation (i.e., an SOA of 0 msec) or in one of the following refresh cycles, resulting in SOAs of approximately 12 msec for the following cycle, 22–23 msec for the second refresh cycle after final target presentation and so forth. The probe stimuli were displaced by a minimum of ±0.2° from the VP of the target. Probe displacement from the VP was increased in steps of ±0.39°. Positive and negative numbers indicate displacement in the direction of motion and opposite to the direction of motion, respectively.

Procedure. The participants sat in a dimly lit room 50 cm from the screen. Head movements were restricted by a chin–forehead rest, and viewing was binocular. The observers received about 40 practice trials and were instructed to pursue the target with their eyes. Physically, the probe stimulus and the target were simultaneously visible only with a 0-msec SOA. However, a previous study (Kerzel, 2000) had shown that for some time after physical target offset, observers perceived target and probe stimulus to be simultaneously visible. Thus, the observers were asked to indicate the relative probe position with respect to the persisting target image. The observers pressed a left or a right key to indicate that the probe stimulus was to the left or the right of the physically final target position (i.e., the persisting or actual target image), respectively. Once a response had been obtained, the next trial was initiated after an intertrial interval of 0.75 sec. During this time, the participants were free to look at any point on the display. No feedback was provided.

Design. The SOA between the last presentation of the target and the onset of the probe varied among 0 and 23 msec. The probe stimuli were displaced by ±0.98°, ±0.59°, and ±0.2° from the VP of the target. The target stimulus moved at a speed of 4.2 deg/sec, 8.4 deg/sec, or 16.8 deg/sec. The 18 combinations of SOA, probe stimulus position, and velocity were fully crossed with five possible VPs and two possible directions of motion (left and right), for a total of 360 trials.

Results

To estimate the point at which the observers perceived the target to vanish, the 50% points of subjective equality (PSEs) were computed by a PROBIT analysis (Finney, 1971; Lieberman, 1983) for every participant and combination of SOA and velocity condition. To this end, the data were collapsed across VP and direction of motion, leaving 10 data points for each combination of SOA and probe condition. PSE values indicate where the observers perceived the physical target offset with respect to the actual VP. Negative PSEs indicate a displacement opposite to the direction of motion, whereas positive PSEs indicate displacement in the direction of motion.

Mean PSEs are shown in Figure 2. A two-way analysis of variance (ANOVA; SOA × velocity) confirmed that PSEs increased from −0.05° with a 0-msec SOA to 0.13° with a 23-msec SOA [$F(1,7) = 93.94$, $MS_e = 0.004$, $p < .0001$]. PSEs increased with velocity from −0.01° for 4.2 deg/sec to 0.07° for 16.8 deg/sec [$F(2,14) = 6.73$, $MS_e = 0.005$, $p < .009$]. Importantly, the interaction of SOA and velocity reached significance [$F(2,14) = 13.19$, $MS_e = 0.005$, $p < .0006$], showing that the difference between PSEs with a 0-msec SOA and a 23-msec SOA differed as a function of velocity. The difference was 0.07°, 0.15°, and 0.31° for velocities of 4.2, 8.4, and 16.8 deg/sec, respectively.

Discussion

Very briefly after physical target offset, the subjective position of the target was shifted in the direction of motion. The size of the shift increased with target velocity. Since the target was subjectively visible during this time interval, it has to be concluded that the velocity of the eye movement determined the perceived position of the target. Since the effects of velocity were present when the target was subjectively visible, the effects of velocity on displacement are at least partially perceptual. With fast target velocity, the pursuit eye movements were faster, so that a larger distance was covered during the SOA of 23 msec. Therefore, the shift of PSE increased with velocity. The observed displacement values are in good agreement with the shift that would be expected if the eye continued to move at target velocity: 0.096°, 0.193°, and 0.386° for velocities of 4.2, 8.4, and 16.8 deg/sec, respectively. Numerically, the observed displacement was smaller than the values expected on target velocity. The reduced displacement is consistent with the observation that the eye usually lags behind the target—that is, the ratio of smooth pursuit velocity and target velocity is smaller than one

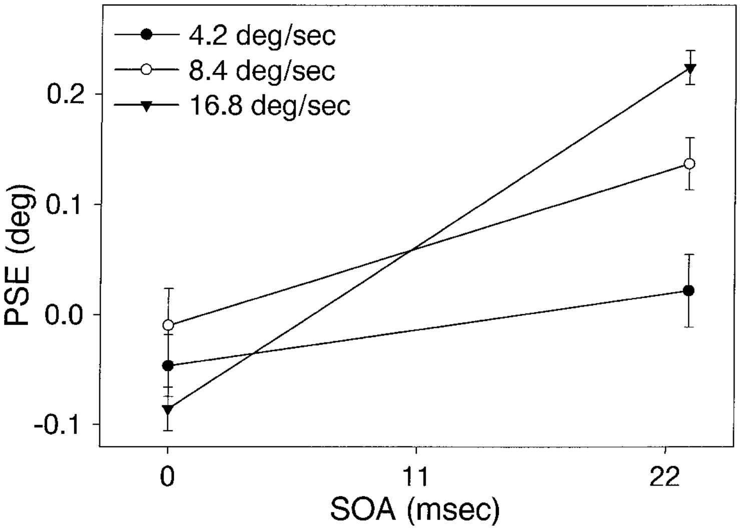

Figure 2. Points of subjective equality (PSEs) in Experiment 1 as a function of stimulus onset asynchrony (SOA) between target and probe onset and of target velocity. Positive and negative numbers indicate a shift in and opposite the direction of motion, respectively.

which necessitates catch-up saccades (e.g., Engel, Anderson, & Soechting, 1999). The claim that the velocity of the overshooting eye movement determines the size of the displacement is further supported by the finding that, in the absence of smooth pursuit, effects of target velocity disappear (Kerzel et al., 2001).

EXPERIMENT 2
Expectation

To study the effects of expectation on localization of the final target position, Hubbard and Bharucha (1988) used predictable reversals of target movement. The target approached the inner surface of a frame, made contact with it, and then moved in the opposite direction. The sequence looked like a ball "bouncing" between two walls. When the target disappeared after having touched the wall—that is, on its way to the opposite wall—the standard forward shift in remembered position was obtained. In contrast, when the target vanished at the time it made contact with the wall, the localization error was reversed—that is, the target was localized in the direction opposite to the actual direction of motion. Thus, displacement did not follow the actual, but the anticipated direction of motion.

Kerzel et al. (2001) already pointed out that the displacement pattern observed by Hubbard and Bharucha (1988) parallels the oculomotor control pattern of pursuit eye movements. Predictable changes of motion direction are anticipated by eye movements that ensure synchronization with the target after the change by reducing the velocity of the eye movement before the direction change (Boman & Hotson, 1992; Dodge, Travis, & Fox, 1930; Kowler, 1989). For instance, if the target reverses its direction, anticipatory eye movements drive the target off the fovea and the eye movement slows down, and when the target starts to move in the opposite direction, "catching up" with the target is facilitated.

Thus, if eye movements play a role in the displacement of the last-seen target position, differences in displacement of the persisting target image as a function of VP should result. When pursuing a target that "bounces" between two positions, observers will most likely anticipate the direction reversals by reducing the velocity of the eye movement at the point of reversal. Thus, overshoot after target offset is expected to be smaller, and consequently, displacement of the persisting target image is expected to decrease.

Method

Participants. Fourteen 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. Eye movements of 5 observers (including the author) were recorded.

Stimuli. The stimuli and procedure were the same as those in Experiment 1, with the following exceptions. Two experimental conditions were realized. Eye movements were recorded in one condition, but not in the other. The stimuli varied slightly between the two conditions.

In the group without eye monitoring, the observers were seated 50 cm from the screen, and the low refresh rate (85 Hz) was used. The target stimulus appeared 12° left or right of the screen center and moved to the opposite side at a velocity of 16.8 deg/sec. At 12° on the other side, it reversed its trajectory. Thus, the target appeared to bounce between the two reversal points at 12° on the left and the right. The target vanished either at a random point along the trajectory within 7.5° of the screen center or at one of the reversal points. The target reversed its direction up to four times. The SOA between the last presentation of the target and the onset of the probe varied between 0 and 23 msec. The probe stimuli were displaced by ±0.98°, ±0.59°, and ±0.2° from the VP of the target. The target disappeared either at the reversal point or at a random point along the trajectory.

In the group with eye movement recording, the observers were seated 55 cm from the screen, and the high refresh rate (96 Hz) was used. The trajectory length was 20°, and the target disappeared either at the reversal points or within 6.3° of the screen center. The target velocity was 17.2 deg/sec, so that a reversal occurred approximately once every 1,170 msec. Probe spacing was ±0.15°, ±0.45°, and 0.75°. The SOA varied between 0 and 22 msec. To reduce the number of eye blinks, the luminance of the background was reduced to light gray.

The 24 combinations of SOA, probe stimulus position, and VP were fully crossed with five possible numbers of reversals (0–4) and two possible directions of initial motion (left and right), for a total of 240 trials.

Apparatus and Procedure. The apparatus was the same as that in Experiment 1 with the following exception. In one group of observers, the horizontal position of the left eye was monitored with a head-mounted, infrared, light-reflecting eyetracker (Skalar Medical, IRIS Model 6500). The analog signal was digitized at a rate of 250 Hz by a DataTranslation A/D–D/A converter (DT 2821). The observers' heads were immobilized with a bite bar. The position of the infrared, light-reflecting sensor was adjusted until the output of the eyetracker was an approximately linear function of gaze direction. Calibration was performed by having the observers look at five equally spaced points that covered 20°. After 120 trials, a short break was given, and the apparatus was recalibrated.

Results

Manual responses were treated as in Experiment 1. Mean PSEs are shown in Figure 3.

Group without eye movement recording. A two-way ANOVA (SOA × VP) confirmed that PSEs increased from −0.15° with a 0-msec SOA to 0.01° with a 23-msec SOA [$F(1,7) = 18.57$, $MS_e = 0.013$, $p < .0026$]. PSEs were displaced to a larger degree opposite the direction of motion when the target vanished at a reversal point [−0.13° vs. −0.01°; $F(1,7) = 20.55$, $MS_e = 0.006$, $p < .0019$]. Importantly, SOA and VP interacted [$F(1,7) = 19.4$, $MS_e = 0.004$, $p < .0023$], indicating that the shift of PSE from 0-msec SOA to 23-msec SOA was smaller for targets that disappeared at a reversal point (0.07° vs. 0.25°).

Group with eye movement recording. A two-way ANOVA confirmed that PSEs increased from −0.10° with a 0-msec SOA to 0.03° with a 22-msec SOA [$F(1,4) = 9.83$, $MS_e = 0.009$, $p < .035$]. Importantly, SOA and VP interacted [$F(1,4) = 17.5$, $MS_e = 0.003$, $p < .0139$], indicating that the shift of PSE from 0-msec SOA to 23-msec SOA was smaller for targets that disappeared at a reversal point (0.01° vs. 0.21°).

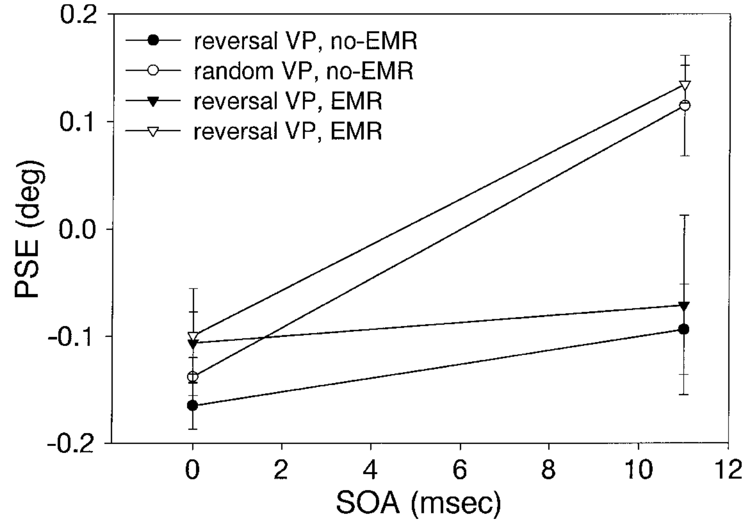

Figure 3. Points of subjective equality (PSE) in Experiment 2 as a function of stimulus onset asynchrony (SOA) between target and probe onset, vanishing point (VP), and eye movement recording (EMR). The target disappeared either at a reversal point or at a random point along the trajectory. Positive and negative numbers indicate a shift in and opposite the direction of motion, respectively.

The eye position data was differentiated with respect to time to obtain velocity data. Because of the high level of system noise with the IRIS eyetracker, it was necessary to filter the velocity data. A low-pass, zero phase shift, second order Butterworth filter with a cutoff frequency of 50 Hz was used. To detect catch-up saccades during smooth pursuit, an acceleration criterion (outside ±3 deg/sec^2 in a 12-msec window [= 3 eye position samples])[1] was used. Saccades were removed, and the missing velocity values were linearly interpolated from the adjacent data points. Trials were collapsed across left and right starting positions after reversing the sign of the velocity data for right starting positions. The data were visually inspected to eliminate trials with eye blinks that were not removed by the acceleration criterion. This was the case in fewer than 1% of the trials. Mean velocity and 95% confidence limit of the smooth pursuit eye movement for each observer is shown in Figure 4. Note that because of the variable length of the trials, the number of measurements for one data point in the graph decreased with time.

Discussion

The size of the target shift briefly after physical target offset differed between the two types of VP. The shift of the perceived target location was smaller when the target vanished at one of two predictable reversal points, as compared with random VPs along the trajectory. As is evident in Figure 4, the velocity of the eye movement was reduced when the target approached a reversal point and was close to zero at the reversal point. Similar to the effect of velocity in Experiment 1, decreasing the velocity of the pursuit eye movement at the reversal points reduced the shift of the target's persisting image briefly after target offset: Because the velocity of the eye movement was lower, the overtracking response was smaller at the reversal points than at a random position along the trajectory. Since the observers still perceived an image of the target for the time intervals investigated here, high-level memory-related explanations do not apply.

Thus, the effects of expectation are at least partially perceptual. Expectations control eye movements and therefore determine where the persisting image of the target is shifted. In contrast, memory theorists have assumed that expectations channel the mental extrapolation of target motion into the expected direction (Freyd & Finke, 1984; Hubbard, 1995b)—that is, the automatic, forward extrapolation of the target motion was assumed to be modulated by knowledge about the target's trajectory. In the perceptual account, the role of expectation is quite similar, in that expectations are assumed to modulate the process causing the displacement. However, the perceptual account assumes that the causal process is perceptual, not memory related. Since the observers perceived the target to be still present during the time intervals used here, the assumed perceptual locus of the distortion may be more appropriate.

EXPERIMENT 3A
Friction

Hubbard reported that the forward shift of the final position of a moving object was reduced when the object appeared to slide along a surface (Hubbard, 1995a, 1998; see

Figure 5). The reduction of forward displacement was taken as evidence for representational friction. From the point of view of perceptual approaches to the localization error, it is hard to see why a reduction of the displacement should occur as long as observers accurately tracked the target. Therefore, it may be possible that the effect of friction does arise from postperceptual processing. If this is the case, no effect of friction should emerge briefly after target offset while the target is still visible, but a reduction of the forward shift should be observed after the target has subjectively vanished (i.e., more than 60 msec after physical offset). To test this hypothesis, Hubbard's (1995a) Experiment 2 was replicated as closely as possible. In addition to the probe judgment task employed in Experiments 1 and 2, the observers were asked to indicate the last position of the target by placing a cursor on the position at which they thought the target had vanished. The cursor appeared 0.5 sec after target offset, so that there was ample time for memory-related processing to take effect.

Method

Participants. Eleven 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, Stimuli, and Procedure. The apparatus, stimuli, and procedure were the same as those in Experiment 1, with the following exceptions. There were two types of friction surface: target only (TO) and surface below (SB). On TO trials, the target was the only element on the screen, apart from the frame that reduced the horizontal extent of the display window to 33.5° (26.67°; the values used in Hubbard, 1995a, are given in parentheses). On SB trials, a filled black surface was drawn below the axis of motion. It was 16° (16.67°) wide and 15.8° (9.92°) tall and was centered between the left

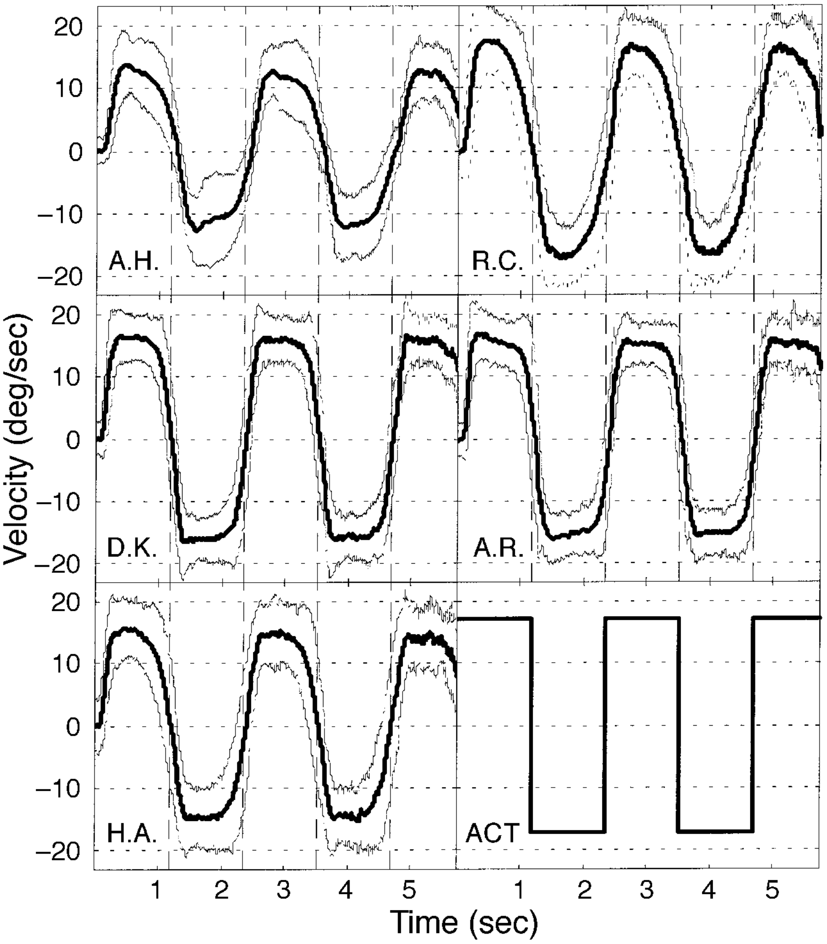

Figure 4. Mean velocity of smooth pursuit eye movements are indicated by the solid lines. The dotted lines indicate 95% confidence limits of the mean. Positive and negative values indicate opposite horizontal directions of the eye movement (left or right). Since the length of the trials was variable, the number of observations per data point decreases with time. The vertical dashed bars indicate when the target reversed its direction of motion. The actual velocity of the stimulus is presented in panel ACT. Data from 5 observers (A.H., R.C., D.K., A.R., and H.A.) are presented.

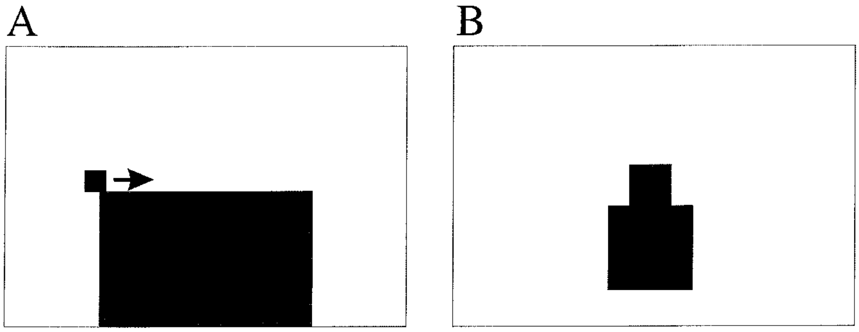

Figure 5. (A) Display used in Experiment 3. A large friction surface (the large black rectangle) was presented. A moving target (the small black square) appeared to slide along the surface. Observers mislocalized the target in the direction of motion and slightly downward. In Experiment 3B, the observers were instructed either to follow the target or to fixate one of the corners. (B) A small rectangle was presented next to a large rectangle in Experiment 4. The observers were instructed to place a mouse cursor on the center of the small rectangle. Judgments were shifted toward the context element.

and the right edges of the screen. The bottom of the surface coincided with the bottom of the screen. The target appeared at the left or the right display window and disappeared randomly at one of five VPs. For right-to-left (left-to-right) motion, the first VP was 75 min (85 min) inside the right (left) vertical boundary of the surface. Each successive VP was located 75 min (75 min) further toward the opposite boundary of the surface. The target stimulus was a 50-min (50-min) filled black square. The target and the surface were adjacent—that is, there was no surface visible between the target and the surface, and the target and the surface did not overlap. The target moved at 12 deg/sec (12.5 deg/sec), a velocity comparable to the velocity that had yielded maximal differences between TO and SB in Hubbard (1995a). In the probe judgment task, a probe stimulus equal to the target appeared 1.13° (center to center) above the target stimulus. It was displaced by a certain distance in or opposite the direction of motion. The participants had to indicate whether they saw the probe stimulus to the left or to the right of the target by pressing a right or a left key. In the cursor adjustment task, no probe stimulus was presented. Instead, a cross-hair cursor appeared at the center of the screen 0.5 sec after target offset. The participants were asked to adjust its position to be identical with the last position of the target. Position judgments were confirmed by a left mouse click.

Task (probe judgment or cursor adjustment) was blocked, and the order of presentation was balanced across participants. From 1 participant, data was collected only in the cursor adjustment task. In the probe judgment task, the SOA between the last presentation of the target and the onset of the probe varied between 0 and 31 msec. The probe stimuli were displaced by ±0.81°, ±0.49°, and ±0.16° from the VP of the target. Either the friction surface was visible, or the background was white. The 24 combinations of SOA, probe stimulus position, and surface type were fully crossed with five VPs and with two possible directions of initial motion, for a total of 240 trials. In the cursor positioning task, the two surface types were crossed with five VPs and two possible directions of motion. Each condition was presented 12 times, for a total of 240 trials.

Results

Data from the probe judgment task were treated as in Experiment 1. A two-way ANOVA (SOA × friction surface) confirmed that PSEs increased from $-0.04°$ with a 0-msec SOA to 0.27° with a 23-msec SOA [$F(1,9) = 114.07$, $MS_e = 0.008$, $p < .0001$]. The displacement was not significantly reduced in the presence of a surface [0.1° vs. 0.13°; $F(1,9) = 1.93$, $MS_e = 0.007$, $p < .1979$].

Data from the cursor adjustment task were treated as follows. Deviations of the adjusted cursor position from the actual VP were determined. The deviation along the horizontal direction of motion is referred to as *M-displacement*; 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. M-displacement did not differ between TO and SB [0.74° vs. 0.64°; $t(10) = 1.12$, $p < .2872$]. Overall, M-displacement was different from zero [0.69°; $t(10) = 5.17$, $p < .0004$]. O-displacement was more negative in SB than in TO [$-0.23°$ vs. $-0.11°$; $t(10) = 3.53$, $p < .0054$]. O-displacement was significantly different from zero in SB [$t(10) = -3.32$, $p < .0077$] and in TO [$t(10) = -2.82$, $p < .0182$].

Discussion

Surprisingly, the reduction of M-displacement in the presence of a friction surface was not obtained in the cursor adjustment task. Similarly, the forward shift was not reduced in the probe judgment task. This result is at odds with previous reports of effects of friction on displacement (Hubbard, 1995a, 1998). However, the absence of an effect of friction is consistent with the perceptual account proposed here. As long as observers track the target, eye movements overshoot the final target position and carry the persisting image into the direction of motion. Thus, the presence of a friction surface should be irrelevant for displacement of the final position.

Consistent with previous studies (Hubbard, 1995a, 1998; Hubbard & Ruppel, 1999) the final position was localized toward the friction surface. This effect has been explained with reference to memory averaging (Hubbard, 1995a,

1998) and landmark attraction (Hubbard & Ruppel, 1999) and is further examined in Experiment 4.

EXPERIMENT 3B
Pursuit Versus Corner Fixation

A memory-related approach has difficulty in explaining why the effect of friction was not obtained in Experiment 3A. In contrast, a perceptual approach offers an explanation. If eye movements produce the localization error, differences in eye movement behavior should explain the differences. For instance, it may have been the case that different observers followed different strategies when confronted with the displays. Whereas the observers in the present experiment abided by the instruction to follow the target with their eyes, the observers in Hubbard's studies may not have done so. When the friction surface was present, the observers may have occasionally fixated the friction surface. In TO trials, the absence of a second object on the screen made it easy to follow the instruction to watch the target. In fact, it may have been difficult not to follow the target in the absence of a second element on the screen (see Kerzel, 2000, on observers' spontaneous tendency to follow a moving target). To test this claim, the observers' eye movement behavior was manipulated via instruction. The observers were told either to follow the target with their eyes, as in Experiment 3A, or to fixate the corner of the friction surface close to where the target appeared. In both conditions, the friction surface was present. A reduction of M-displacement is expected in the fixation condition, because the oculomotor overshoot should be absent or reduced, so that a shift of the persisting target image should not occur.

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, Stimuli, and Procedure. The apparatus, stimuli, and procedure were the same as those in Experiment 3B. Only the cursor positioning task was run. The friction surface was always visible. The observers were instructed either to follow the target with their eyes or to look at the corner of the friction surface close to the target.

The two eye movement instructions were crossed with five VPs and two possible directions of motion. Twelve repetitions were collected in either eye movement condition, for a total of 480 trials. Eye movement condition (corner fixation or pursuit) was blocked, and the order of presentation was balanced across participants.

Results

Data treatment was as in Experiment 3A. M-displacement was reduced when the participants were instructed to look at a corner of the friction surface [$-0.21°$ vs. $0.55°$; $t(7) = 4.79$, $p < .002$]. M-displacement with pursuit deviated significantly from zero [$t(7) = 4.34$, $p < .0034$], but not with corner fixation [$t(7) = -1.29$, $p > .23$]. O-displacement in the pursuit condition was less negative than with corner fixation [$-0.15°$ vs. $-0.39°$; $t(7) = 3.53$, $p < .0096$]. O-displacement in both the pursuit [$t(7) = -2.78$, $p < .0274$] and the corner fixation [$t(7) = -3.8$, $p < .0067$] conditions was different from zero.

Discussion

In the pursuit condition, the size of the forward shift was comparable to that in the previous experiment (0.55° vs. 0.69°). When the observers were instructed to look at the corner of a rectangular friction surface close to where the target entered the friction surface, however, M-displacement was reduced. Since the targets always disappeared after having entered the friction surface and fixation was at the corner close to target appearance, the reduction indicates that the observers localized the target toward the fovea. Furthermore, negative O-displacement was increased with fixation. Because in the corner fixation condition, the observers looked at a position slightly below the target's trajectory, the reduction of O-displacement also indicates localization toward the fovea. The bias to localize peripheral stimuli toward the fovea has been reported before (e.g., Van der Heijden et al., 1999). In sum, the instruction to look at a corner of the friction surface had strong effects on the pattern of localization. Thus, presentation of a friction surface may have induced the observers in Hubbard (1995a, 1998) to follow the target less accurately than in TO trials. Instead of pursuing the target, they may have fixated parts of the surface. The differences resulting from different eye movement instructions show that participants may switch between pursuit and corner fixation and that it is a strategic decision whether they perform one or the other. The particular choice of fixation point—that is, the corner close to where the target entered the friction surface—appears to be the most plausible, given that the observers were also motivated to localize the target's final position accurately and the target vanished close to this corner (within 5×75 min = 6.25° of the corner). Taken together, the results suggest that the friction surface did not act as a brake on the mental representation of the target. Rather, it provided observers with a fixation point; therefore, it acted as a "brake" on eye movements.

EXPERIMENT 4
Memory Averaging

In Experiment 3, it was observed that negative O-displacement was increased in the presence of a friction surface below the target. That is, the target was localized farther toward the friction surface than it actually was. This effect has been interpreted as indicating memory averaging of context element and target. It has been obtained for surfaces above, below, left, and right of the target (Hubbard, 1995a, 1998). An interpretation in terms of memory averaging presumes that the position of the target is perceived accurately before the target vanishes. In particular, perception of the center of the target element should not be affected by the context. When participants are asked to adjust the cursor position to be identical with the last-seen target position, they presumably position the cursor over the remembered target center. To examine whether the observers' perception of the target center is affected by a context element that is adjacent to the target, the observers were asked to adjust the cursor to be identical with the center of a target while the target was visible.

Method

Participants. Nine right-handed 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, Stimuli, and Procedure. The apparatus, stimuli, and procedure were the same as those in Experiment 1, with the following exceptions. The target was a 2° filled black square. To cancel out effects resulting from asymmetrical handling of the mouse (e.g., dragging the mouse down may be easier than moving it up), the target position was varied. The target's center was positioned on one of two virtual circles (diameters of 6° and 12°) around the center of the screen. The target appeared in 1 of 10 possible positions on the virtual circle. Successive positions were separated by 36° of rotation, starting at the 3 o'clock position. The context element was a 4° square that was positioned next to the target square. Between target and context element, there was no background visible, but target and context did not overlap. The context element was either above, below, left, or right of the target. A red-filled circle with a diameter of 0.13° served as cursor. It always appeared at the screen center. The participants were instructed to position the cursor on the center of the target and to confirm the cursor adjustment with a left mouse click. If no response was obtained within 3 sec after display onset, an error message indicating a time-out error appeared. The time limit allowed for accurate adjustment of the cursor but prevented usage of external aids, such as the hands, to solve the task. When the final cursor position was outside the target element, an error message appeared, and the trial was repeated at a random position in the remainder of the block. Each trial was started by a right mouse click.

The four possible context placements (above, below, left, or right of the target) and the 20 target positions were fully crossed. Two repetitions of each condition were collected, for a total of 160 trials.

Results

Mean response time was 1.8 sec. In 0.8% of all the trials, a time-out error occurred, and in 0.07% of all the trials, the target was missed. The deviation of the cursor adjustment with respect to the target center was determined. For the horizontal deviation, negative and positive values indicate that the cursor was positioned to the left and the right of the target's center, respectively. For the vertical deviation, negative and positive values indicate that the cursor was positioned lower and higher than the target's center, respectively. Context effects were evaluated along the axis of displacement (vertical or horizontal). A context element on the left produced displacement to the left [$-0.058°$; $t(8) = -3.56$, $p < .0074$], whereas a context element on the right produced a bias to the right [0.07°; $t(8) = 4.02$, $p < .0038$]. A context above the target produced an upward bias [0.085°; $t(8) = 4.16$, $p < .0032$], whereas a context below produced a downward bias [$-0.084°$; $t(8) = 7.45$, $p < .0001$]. Differences between context elements displaced along the horizontal axis [0.12°; $t(8) = 8.44$, $p < .0001$] and along the vertical axis [0.17°; $t(8) = 7.21$, $p < .0001$] were significant. Collapsed over context elements, there was a bias neither along the horizontal axis [0.007°; $t(8) = 0.47$, $p > .6$] nor along the vertical axis [0.0003°; $t(8) = 0.03$, $p > .9$]. As a summary index of context effects, the deviation from the target center toward the context element was determined across context positions. Deviations toward the context element received a positive sign; deviations away from the context element received a negative sign. Mean deviation toward the context element was significantly different from zero [0.07°; $t(8) = 8.09$, $p < .0001$].

Discussion

The observers judged the center of a square stimulus to be closer to an adjacent context element than it actually was. This tendency was present along the horizontal and vertical dimensions. One may hypothesize that some Gestalt-like organization of target and context produced a shift of the target center toward a common center. It may be that the location of the common center was predicted by the center of a circle inscribed by target and context, similar to what has been reported for the center of mass of convex polygons (Baud-Bovy & Soechting, 2001). Thus, even if the observers in Experiment 3 had perfectly accurate memories of the final target position, a bias to localize the target toward the context element would have been observed. Because perception precedes memory and memory takes the results of perception as input, the locus at which the distortion arises cannot be exclusively memory related. Rather, the origin of *memory averaging* is partially or completely perceptual. Furthermore, the present experiment shows that the effects of representational gravity may be exclusively postperceptual. Across all context conditions, there was no bias to localize the target center farther down than it actually was. Although conclusions from null effects should be treated with caution, one may tentatively suggest that there is no perceptual analogue of gravity, so that the downward shift in memory tasks is exclusively due to high-level memory processes.

EXPERIMENT 5A
Weight

The rationale of Experiment 4 was applied to effects of weight reported by Hubbard (1997). Hubbard (1997) found that the final position of moving targets was shifted along the axis of gravitational attraction—that is, downward. This tendency increased with target size. Large targets showed more downward displacement than did small targets. If the reported bias was due exclusively to postperceptual processing, pointing to the center of a target should be unaffected by its size. In contrast, if effects of mass are (partially) perceptual, a trend to localize the center of large visible targets farther down than the center of small visible targets should be observed.

Method

Participants. Sixteen right-handed 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, Stimuli, and Procedure. The apparatus, stimuli, and procedure were the same as those in Experiment 4, with the following exceptions. A filled black circle was used as target, and no context element was present. Its diameter varied between 1°, 2°, and 3°, which is approximately the same range as in Hubbard (1997), who presented diameters of 0.83° to 2.5°.

The three diameters were crossed with ten angular positions around one of two virtual circles. Each of the 60 unique conditions was presented once in two consecutive blocks, for a total of 120 trials.

Results

Mean response time was 2 sec. In 2.3% of all the trials, a time-out error occurred, and in 0.2% of all the trials, the target was missed. The deviation of the adjustment cursor from the center of the target was determined as in Experiment 4. A one-way ANOVA showed that the horizontal deviation decreased with target diameter [$F(2,30) = 6.21$, $MS_e = 0.0002$, $p < .0055$]. Mean horizontal deviation was 0.0143°, 0.0099°, and −0.0016° for diameters of 1°, 2°, and 3°, respectively. Overall, horizontal displacement was biased toward the right [0.006°; $t(15) = 2.66$, $p < .0178$]. A second one-way ANOVA showed that the vertical deviation increased with radius [$F(2,30) = 5.39$, $MS_e = 0.0002$, $p < .01$]. Mean vertical displacement was −0.0024°, −0.0167°, and −0.0175° for diameters of 1°, 2°, and 3°, respectively. Overall, vertical displacement was biased downward [−0.012; $t(15) = -2.22$, $p < .0423$].

Discussion

The results show that the observers were highly accurate at pointing toward the center of a circular stimulus. The deviations from the actual center were below the resolution of the display (1 pixel = 0.03°)—that is, the error was smaller than 1 pixel. Nonetheless, the results show that as the size of a circular stimulus was increased, the perceived center of the stimulus was shifted progressively downward. Thus, the effects of mass reported by Hubbard (1997) are not due exclusively to memory-related processes. Because the size of the effect was larger in Hubbard (1997), one would have to assume that the perceptual distortion was magnified in memory or that a mental analogue of weight contributed to the distortion. Also, across sizes, the deviation between actual and judged center of the target circle was significantly negative—that is, the center was localized farther down than the actual center. However, because no such downward shift was obtained in the previous experiment, the effect should be interpreted with care. On the other hand, the downward bias is consistent with previous reports of biases in judgments of the center of mass. Bingham and Muchisky (1993a, 1993b) found that participants who had to grasp the "stable point" of a wooden shape with a tong showed a tendency to grasp a location slightly below the actual center of mass.

A discrepancy that needs further clarification is why Hubbard (1997) did not find an effect of weight when he asked observers to judge the position of a stationary target after it had vanished. Inspection of Figure 3 in Hubbard (1997) shows that there is a slight numeric tendency for O-displacement to decrease with increases in target size. However, this effect was not significant. It may have been the case that motor variance from the mouse-pointing procedure was higher in Hubbard (1997). In his study, no attempts to cancel out effects of asymmetrical mouse handling were reported.

EXPERIMENT 5B

To clarify whether an effect of mass on memory for the final position of a stationary target may be obtained with the method used in Experiment 5A, the temporal parameters were changed. The target was visible for 1.5 sec, and after a retention interval of 0.5 sec, the observers had to point to the center of the target. Thus, the perceptual task was changed to a memory task.

Method

Participants. Eleven right-handed 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, Stimuli, and Procedure. The apparatus, stimuli, and procedure were the same as in Experiment 5A, with the following exceptions. The target was visible for 1.5 sec. After a retention interval of 0.5 sec, the cursor appeared, and the participants were instructed to point to the remembered final position. For compatibility with the methods of Hubbard (1997), no feedback about whether participants had missed the target was given, and response time was unconstrained.

Results

Mean response time was 3.6 sec. The cursor was positioned outside the target in 8% of the trials, indicating that localization of a remembered target location was more difficult than localization of a visible target. The deviation of the adjustment cursor from the center of the target was determined as in Experiment 5A. A one-way ANOVA did not show any effects of size on horizontal deviation ($F < 1$). Mean horizontal deviation was 0.3° and did not deviate from zero ($p > .16$). A second one-way ANOVA showed that the vertical deviation increased with radius [$F(2,20) = 4.52$, $MS_e = 0.061$, $p < .024$]. Mean vertical displacement was −0.11°, −0.16°, and −0.18° for diameters of 1°, 2°, and 3°, respectively. Overall, vertical displacement was biased downward [−0.15; $t(11) = -3.04$, $p < .0124$].

A mixed factor ANOVA on vertical displacement, with experiment (Experiments 5A and 5B) as between-subjects factor, showed a significant effect of experiment [$F(1,25) = 11.29$, $MS_e = 0.033$, $p < .0025$] and size [$F(2,50) = 9.28$, $MS_e = 0.068$, $p < .0004$] and a significant interaction between size and experiment [$F(2, 50) = 3.54$, $MS_e = 0.068$, $p < .037$]. The interaction showed that the effect of target size was more pronounced in the memory task than in the perceptual task.

Discussion

The present experiment shows that the increase in downward displacement observed in a perceptual task in Experiment 5A may also be obtained when the position of the target has to be retrieved from memory. Therefore, the failure to find an effect of size on memory of a stationary object reported in Hubbard (1997) may be due to the specific procedure used. In particular, motor variance arising from handling the mouse may have masked the effect. The comparison of Experiments 5A and 5B shows that the size of the effect was larger in the memory variant of the task. Thus, it may be that the perceptual distortion is magnified in memory. Alternatively, one may assume that some mental analogue of weight exists. However, memory can be ruled out as the sole locus of the distortion.

GENERAL DISCUSSION

Deviations from the actual VP of a moving stimulus in various directions have been attributed to representational momentum, friction, weight, and processes related to expectation and memory averaging (for an overview, see Hubbard, 1995b). In these studies, it was implicitly assumed that the perception of the final target position was accurate and that systematic distortions occurred because of post-perceptual processing. In the present series of experiments, a number of effects previously attributed to memory displacement were reconsidered, and evidence for a perceptual locus of the distortions was provided. Logically, perceptual errors have to be reflected in memory because memory takes perceptual output as input. Therefore, if similar errors occur in perception and memory, the locus of the distortion cannot be restricted to memory but is at least partially perceptual. However, if similar error patterns occur in memory and perception, no firm conclusions can be drawn with respect to the memory processes that are involved. Probably, memory magnifies or minimizes perceptual errors, or memory contains mental analogues of physical principles that add to the perceptual distortion. To determine the exact nature of the memory processes involved is a matter for future research.

Consistent with the assumption that *memory displacement* is partially perceptual in nature, effects of velocity and expectation were observed while the target was subjectively still visible (Experiments 1 and 2). Previous studies (Kerzel, 2000) had shown that the target image persisted for about 50–60 msec after physical offset of the target. Thus, any effects observed during this period have to be attributed to perception—in particular, to eye movements that shift the persisting image in or opposite the direction of motion. Experiment 3 showed that the effects of a friction surface on memory displacement may depend on whether observers follow the target with their eyes or not. In the presence of a friction surface, observers may have fixated points on the surface, which was not likely to occur when only a single element, the target, was presented. Experiment 4 demonstrated that the judged center of a square target was shifted to an adjacent context element. This demonstrates that memory averaging has a (partially) perceptual origin. Also, the judged center of a circular target was shifted increasingly downward, which matches the observed effects of representational weight. In sum, perceptual effects have been observed for a number of variables that were supposed to be memory related. Therefore, the locus of memory displacement cannot be memory exclusively. Rather, perceptual factors may account for a large portion of the observed distortion of the judged final position.

Previously, the distortions of position information occurring when observers were confronted with dynamic objects were attributed exclusively to memory-related processing stages. However, there is growing evidence that this may not be entirely the case, mainly because one of the grounding assumptions of the view is rather shaky. Implicitly, memory theorists assume that perception provides the mental apparatus with an accurate description of the environment. A long tradition of research, however, has demonstrated that this is not the case. Among others, Gibson (e.g., 1966, 1979) pointed out that the sense organs should not be considered passive receptors that take "pictures" of the environment but, rather, as part of active perceptual systems. The results of Experiments 1–3 may be understood within such a framework. In these experiments, the active control of eye movements produced a distortion of the perceived final position. In Experiment 1, it may be assumed that the observers actively adjusted the velocity of the pursuit eye movement to match the target velocity. Therefore, the persisting target image was carried into the direction of motion by a larger distance at higher velocities. Experiment 2 showed that expectations about the trajectory of a target influence the control of eye movements. Experiment 3 showed that observers are able to make strategic decisions about where to look when they are confronted with a cluttered display.

In the case of memory averaging and the effects of mental analogues of weight (Experiment 5), it is not so much the active nature of perceptual control processes that explains the mislocalization. Rather, distortions in the perception of the center of a stimulus occur. The downward bias is consistent with previous reports of judgments of the center of gravity (Bingham & Muchisky, 1993a,1993b). However, the important thing to note here is that they are observed at a perceptual level, and not at a higher level cognitive stage. When the target position had to be retrieved from memory, the influence of target size was stronger than when the target was visible. Two interpretations of the increase in displacement may be possible. First, there may be mental analogues of weight operating in memory (see Hubbard, 1997) that add to the distortion. Second, memory may magnify an already existing distortion. The assumption of memory-related magnification is corroborated by an effect known as boundary extension (e.g., Intraub, 1997; Intraub & Richardson, 1989). When drawing photographs from memory, observers tend to remember having seen a greater expanse of the scene than was shown. Similar to the magnification of boundaries, one may speculate that the downward bias may be magnified in memory.

The averaging of the center of a target stimulus in Experiment 4 may be related to an effect known as the global effect (e.g., Coeffe & O'Regan, 1987; Findlay, 1982; Findlay & Gilchrist, 1997). When a saccade is executed toward one of two neighboring peripheral targets, the saccadic landing site is somewhat shifted toward the second (irrelevant) element. Perceptual processes and motor programming are involved in the global effect (see, e.g., Findlay & Gilchrist, 1997). Similarly, judgments of the center of the target stimulus were shifted toward the irrelevant context element, which may reflect the same perceptual processes as those underlying the global effect.

In sum, the present experiments support the view that perceptual factors account for a large proportion of a mislocalization that was previously thought to result from processes operating in memory. The results suggest that the active nature of perceptual control and perceptual illusions may be the origin of the error.

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NOTE

1. The acceleration criterion is highly dependent on the high-frequency noise in the data. The more noise, the higher the acceleration criterion that has to be selected. The data were visually inspected to find the most appropriate criterion.

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