

Centripetal Force Draws the Eyes, Not Memory of the Target, Toward the Center

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Many observers believe that a target will continue on a curved trajectory after exiting a spiral tube. Similarly, when observers were asked to localize the final position of a target moving on a circular orbit, displacement of the judged position in the direction of forward motion (“representational momentum”) and toward the center of the orbit was observed (cf. T. L. Hubbard, 1996). The present study shows that memory displacement of targets on a circular orbit is affected by eye movements. Forward displacement was larger with ocular pursuit of the target, whereas inward displacement was larger with motionless eyes. The results challenge an account attributing forward and inward displacement to mental analogues of momentum and centripetal force, respectively.

It has long been known that people hold erroneous beliefs about the laws of motion. For instance, college students frequently report that the trajectory of a moving object will continue to show some curvature after exiting a spiral tube even though the physically correct path is straight (McCloskey, Caramazza, & Green, 1980). Perhaps observers believe that the act of setting an object in motion imparts to the object a force or so-called impetus that serves to maintain its motion in the absence of external forces (McCloskey & Kohl, 1983). In the spiral tube problem, it would act to pull the object toward the center of the tube. Further studies showed that observers’ performance improved when actual motion trajectories were displayed (Kaiser, Proffitt, & Anderson, 1985), suggesting that accurate perceptual representations of the spiral tube situation exist. However, this conclusion was contradicted by studies investigating visual short-term memory of a circular motion path (Freyd & Jones, 1994; Hubbard, 1996).

Research on memory for dynamic events has demonstrated that the judged vanishing point (VP) of a moving target is often displaced from the true VP (memory displacement). Typically, the judged VP is displaced in the direction of anticipated motion (Freyd, 1987; Freyd & Finke, 1984; Verfaillie & d’Ydewalle, 1991). Originally, it was proposed that similar to the momentum of moving objects, the mental system is unable to stop the mental representation of motion instantaneously. Rather, the mental representation of motion continues after target offset. The resulting forward displacement was therefore referred to as *representational momentum* (Freyd & Finke, 1984). For motion in a spiral tube, this forward shift was found to be largest when the target followed a

curved trajectory after exiting the tube (Freyd & Jones, 1994). These results suggested that the anticipated direction of motion after exiting the spiral tube was curvilinear. Therefore, observers’ perceptual representations would not accurately reflect physical regularities.

Internalization of Physical Regularities

This conclusion was challenged by Hubbard (1996), who suggested that the larger forward displacement on the curved trajectory was due to the internalization of centripetal force. Circular motion is specified by a vector \mathbf{v} for forward velocity along the tangent to the orbit and a vector \mathbf{a} for centripetal acceleration toward the center of the orbit (see Figure 1). The vector \mathbf{v} indicates unconstrained target motion, and forward displacement along this line was taken to support the assumption of representational momentum. The vector \mathbf{a} is orthogonal to \mathbf{v} and pulls the target toward the center of the orbit. Displacement along this axis toward the center of the orbit was taken to support the assumption of a representational analogue of centripetal force.

Consistent with the assumption of internalization of momentum and centripetal force, the judged final position of a revolving object was displaced from the true final position in the direction of tangential motion and toward the center of the orbit (Hubbard, 1996). When both the angular velocity of the target and the size of the radius were varied, then increases in either angular velocity or radius size also increased the magnitude of inward displacement. This pattern of results was taken to support the hypothesis of an internalization of centripetal force because the norm of vector \mathbf{a} depends on the norm of vector \mathbf{v} and radius size, r , as

$$|\mathbf{a}| = \frac{|\mathbf{v}|^2}{r}.$$

Furthermore, the lack of an interaction between target velocity and radius was taken to support the analogy between mental and physical centripetal force. However, the multiplicative relation between \mathbf{v} and r would rather suggest that the two variables interact and not add up.

In general, it was suggested (see Hubbard, 1995) that the phenomenal aspects of physical laws have become incorporated into

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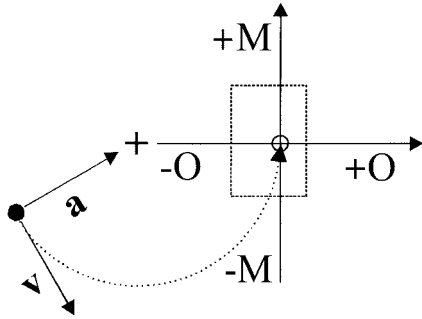


Figure 1. Schematic drawing of the forces and the sign convention. The cross indicates the center of rotation of a target (filled circle) that vanishes at a random location (unfilled circle). The trajectory of the target is indicated by the dotted line. On the left side, the forces specifying circular motion are depicted. When a target moves on a circular orbit, forward motion along the tangent of the orbit is indicated by the vector \mathbf{v} . Acceleration toward the center of the orbit is indicated by the vector \mathbf{a} . Centripetal force depends on the norm of \mathbf{v} and the radius size. On the right side, the sign convention for the deviation of the judged from the actual vanishing point (VP), referred to as memory displacement, is explained. Displacement along the tangent to the orbit is referred to as M-displacement. M-displacement in the direction of tangential motion received a positive sign (+M). M-displacement opposite to the direction of motion received a negative sign (-M). Displacement orthogonal to the tangent, that is, along an axis passing through the true VP and the center of the orbit, was referred to as O-displacement. O-displacement toward the inside of the orbit received a negative sign (-O), and O-displacement toward the outside received a positive sign (+O). All eye movement traces, irrespective of VP and direction of rotation, were transformed such that they were aligned with (a) the actual VP at the origin of the coordinate system and (b) counterclockwise rotation. The dashed box indicates the clipping of the stimulus space that is presented in Figure 2.

the functional architecture of mental representations. Thus, not only momentum and centripetal force, but also gravity, friction, and weight would have become part of our representational system. For instance, the judged VP of a horizontally moving target is typically displaced in the direction of motion and downward, which may be attributed to mental analogues of momentum and gravity, respectively (Hubbard, 1997). Displacement of the judged from the actual VP along the axis of motion is referred to as *M-displacement* and displacement orthogonal to the axis of motion as *O-displacement*. For horizontal motion, M-displacement would shift the judged VP to the left or right of the true VP, and O-displacement would shift the judged VP above or below the true VP. For circular motion, M-displacement would be along the tangent to the circle, and O-displacement would be orthogonal to the tangent (see Figure 1).

Eye Movements and Memory Displacement

Recently, it was suggested that observers' perceptual behavior during stimulus presentation, rather than cognitive processes driven by internalized physical laws, explain some of the distortions of visual short-term memory (for limitations of this account, see the General Discussion section). For instance, when observers were presented with a display showing the smooth linear motion of a target that vanished at a random point along the trajectory, the judged final position was found to be displaced in the direction of

motion (Hubbard & Bharucha, 1988). The distortion was attributed to consequences of mental analogues of momentum. However, an analysis of observers' perceptual behavior during stimulus presentation shows that observers typically engage in smooth pursuit of the target. That is, they try to keep the target in their fovea by smoothly moving their eyes. One consequence is that the eyes overshoot the target's VP: The eyes continue to move in the direction of motion after the target disappears (Kerzel, 2000; Kerzel, Jordan, & Müsseler, 2001; Mitrani & Dimitrov, 1978). Current models of smooth pursuit assume that prospective planning of smooth eye movements extends about 200–250 ms into the future (Vercher, Lazzari, & Gauthier, 1997). As a consequence, the eye would follow a preplanned trajectory for about 250 ms after target disappearance, and gaze direction would be displaced in the direction of motion after target offset. Because previous studies failed to observe displacement of the final target position in the direction of motion when the eyes were motionless (Eagleman & Sejnowski, 2000; Kerzel, 2000; Whitney, Murakami, & Cavanagh, 2000), one may assume that oculomotor overshoot, and not representational momentum, explains the forward shift with smooth stimulus motion.

When effects of centripetal force were studied, circular motion instead of linear motion was used (Hubbard, 1996). Nonetheless, a similar explanation of the observed results in terms of eye movements is possible. Both increases in radius size, r , and rotational velocity, ω , increase the tangential velocity, v , of the target because $v = r\omega$. The tangential velocity determines the distance in degrees of visual angle, d , that the target will travel per time unit, t , as $d = tv$. If the eyes followed the revolving target with approximately equal tangential velocity (Leung & Kettner, 1997), and if there was an oculomotor overshoot lasting about 250 ms, one would have to conclude that the distance covered by the eyes after target offset increases with increases in both radius and angular velocity (cf. Table 1). It should be noted that the relation between rotational velocity and radius is multiplicative, which would result in a statistical interaction of the two factors. Furthermore, the trajectory of the oculomotor overshoot is expected to be bent, because the smooth pursuit system is anticipating the target to move on a circular trajectory.

In sum, there is reason to believe that the eyes would move along a circular trajectory for some time after target offset and that the distance covered during this time would depend in a nonadditive way on both radius and rotational velocity. Expressed in terms of O- and M-displacement, one would expect the eyes to be displaced toward the center of the orbit and in the direction of motion relative to the final target position. To illustrate this point, the simulated target position 250 ms after target offset is shown in Table 1. If the eyes were perfectly aligned with the predicted target position during oculomotor overshoot, these simulated target positions would correspond to the eye position 250 ms after target offset. Clearly, O- and M-displacement increase with increases in rotational velocity and radius size. As there is a strong relation between oculomotor overshoot and memory displacement, one would also expect judgments of the final target position to be dependent on rotational velocity and radius. In particular, the remembered final target position would be displaced toward the center (negative O-displacement) and into the direction of motion (positive M-displacement).

In addition to properties of the oculomotor system, strategic decisions of the observers may have to be considered. Even if

Table 1
M- and O-Displacement in Degrees of Visual Angle as a Function of Radius and Target Velocity

Radius	M-displacement				O-displacement			
	Pursuit		Fixation		Pursuit		Fixation	
	Slow	Fast	Slow	Fast	Slow	Fast	Slow	Fast
2°	0.40 ± 0.09	0.53 ± 0.11	0.11 ± 0.10	0.07 ± 0.13	-0.18 ± 0.08	-0.19 ± 0.10	-0.55 ± 0.19	-0.61 ± 0.19
3°	0.59 ± 0.07	0.78 ± 0.14	0.11 ± 0.15	0.18 ± 0.14	-0.16 ± 0.06	-0.23 ± 0.07	-0.73 ± 0.26	-0.72 ± 0.21
4°	0.79 ± 0.12	1.03 ± 0.17	0.17 ± 0.18	0.18 ± 0.12	-0.21 ± 0.11	-0.37 ± 0.13	-0.90 ± 0.24	-0.86 ± 0.33
5°	0.98 ± 0.16	1.28 ± 0.30	0.14 ± 0.14	0.14 ± 0.19	-0.32 ± 0.15	-0.42 ± 0.11	-1.02 ± 0.41	-1.04 ± 0.41

Note. Group means and between-subjects standard deviations are given in the format $M \pm SD$. The target followed a circular orbit with a radius of 2, 3, 4, or 5° and had either a slow velocity (90° of rotation per second) or a fast velocity (120° of rotation per second). Judgments of the final target position are presented for the two eye movement instructions. Either observers were asked to follow the target with their eyes (pursuit), or they were told to maintain fixation on the screen center (fixation). M-displacement with pursuit was dependent on both radius size and rotational velocity, whereas M-displacement with fixation was independent of these factors. M-displacement with pursuit was always significantly different from zero with pursuit (t tests, $ps < .0001$), whereas significance was marginal with fixation (t tests, $.01 < ps < .18$). O-displacement increased with radius size and rotational velocity with pursuit but depended only on radius size with fixation. O-displacement was significantly different from zero in both conditions (t tests, $ps < .001$). M-displacement = displacement along the tangent (i.e., along an axis passing through the true vanishing point and the center of the orbit) to the orbit; O-displacement = displacement orthogonal to the tangent.

observers had been told to “watch the target until it vanished” (Hubbard, 1996, p. 1051), they may not always have done so. Trial duration was long in the experiments of Hubbard (1996): With the fastest velocity of 40 degrees of rotation per second, trial duration ranged between 9 and 13.5 s, and with the slowest velocity of 13 degrees of rotation per second, it ranged between 27.7 and 41.5 s. Therefore, observers may have shifted their fixation from the target to other points on the display. But where may observers have looked instead? One prominent candidate for the point of fixation is the center of the target’s orbit, as all positions occupied by the target are equidistant from there. Thus, maintaining fixation at the center ensures equal retinal acuity for all positions of the target. In contrast, looking at points outside the trajectory would be very unnatural because the distance between the target and the fovea would become extremely large (i.e., the maximum eccentricity may be more than twice the orbit’s radius).

If observers had looked at the center of the orbit on some trials, the target would be presented in the retinal periphery. Generally, peripheral targets are mislocalized toward the fovea by a certain fraction of their eccentricity (about 10%, van der Heijden, van der Geest, de Leeuw, Krikke, & Müsseler, 1999); that is, the further the target is from the fovea, the larger is the error. The source of this error may be visual short-term memory (Kerzel, 2002b; Müsseler, van der Heijden, Mahmud, Deubel, & Ertsey, 1999; Sheth & Shimojo, 2001). Thus, if observers fixated the orbit’s center, mislocalization toward this point (negative O-displacement) was expected.

In sum, with circular target motion, it may have been the case that observers showed two types of perceptual behavior: Either they followed the target with their eyes, which is what they had been told to do in Hubbard’s (1996) study, or they deviated from the instruction and looked at other points in the display. With circular motion, it is more likely that points inside the orbit were fixated than points on the outside.

Aim of Study

The aim of the following experiment was to isolate these two possible perceptual behaviors and study their effects on memory

for the final target position. I suggest that oculomotor behavior during stimulus presentation explains the pattern of memory displacement that was previously attributed to the internalization of momentum and centripetal force. Observers were told either to follow a revolving target with their eyes or to look at the center of the orbit. There were reasons to believe that differential effects on M- and O-displacement arise as a function of eye movement instruction.

When the eyes are motionless, no oculomotor overshoot beyond the target’s VP occurs, whereas strong oculomotor overshoot results when observers pursue the target with their eyes. If the oculomotor overshoot associated with smooth pursuit contributes to the forward shift, M-displacement would be expected to be strongly diminished with fixation of the orbit’s center compared with pursuit of the target. Furthermore, effects of the target’s tangential velocity on M-displacement were expected to occur with smooth pursuit but not with fixation, because the velocity of smooth pursuit follows the tangential target velocity. As the tangential target velocity is determined by radius and rotational velocity, M- and O-displacement with pursuit were expected to depend on these two factors. In contrast, M- and O-displacement should not depend on the tangential velocity of the target when the eyes are fixated on the center of the orbit. Only the orbit’s radius (i.e., the target’s eccentricity) was expected to determine O-displacement because the bias toward the fovea increases with increasing radius size.

This is the first study on memory displacement that measured eye position with a high degree of accuracy. To this end, a high-resolution eye tracker was used that allowed for a detailed analysis of the relation between eye position and remembered target position. Previous studies only measured eye velocity along a single dimension (Kerzel, 2002a; Mitrani & Dimitrov, 1978), which limits conclusions to target motion along a straight path. However, it was hypothesized that memory displacement orthogonal to the direction of motion provides evidence for the internalization of physical principles other than representational momentum (Hubbard, 1996). To evaluate this claim, it was necessary to

measure eye movements along two dimensions: the axis of motion and the axis orthogonal to motion.

Furthermore, measuring eye movements allowed for a major improvement in the judgment procedure: Instead of having observers adjust a cursor on the final target position, observers were asked simply to look at the position where they thought the target had vanished. Thus, a rather pure form of judgment was possible. With cursor adjustment, the initial position of the cursor is known to affect the judgments (van der Heijden et al., 1999) and the whole task is necessarily divided into two parts—a target-perception part and a cursor-perception part. As there is evidence that the two tasks are not independent, the fixation task may be considered an improved procedure.

Method

Participants

Eight students at the Ludwig-Maximilians University of Munich were paid for their participation. All participants had normal vision and were naive as to the purpose of the study.

Apparatus, Stimuli, and Design

Recording of eye movements. A Fourward Technologies Generation 6 Dual Purkinje Image eye tracker (Crane & Steele, 1985) was used. The experimenter supervised data collection online on a master PC, while a slave PC inside the experimental booth served to present the stimuli. The analog signal was digitized at a rate of 500 Hz by a DataTranslation A/D–D/A converter (DT EZ-21). Observers' heads were stabilized with a bite bar and a forehead rest. Offset and gain of the eyetracker output were initially calibrated using the eyetracker hardware and subsequently recalibrated in software. To this end, a small cross was first presented at the center of the screen and then successively at each of the target's VPs. Observers fixated the cross and confirmed their response by key press. This procedure allowed for the most precise calibration of the eyetracker output. In previous studies using a similar fixation-based localization task, the apparatus was calibrated after each trial (e.g., Zivotofsky et al., 1996; Zivotofsky, White, Das, & Leigh, 1998); however, if a stimulus appears at the true VP after observers judged this VP, observers may notice the deviations between the foveated position and the calibration mark. To avoid this kind of feedback and subsequent perceptual learning, the relation between judged VP and actual VP was obscured. To this end, the apparatus was calibrated only after four consecutive trials. During calibration, the VPs of the four preceding trials were presented in a different random order.

Stimuli. The stimuli were created using a Matrox Millennium II graphics card controlled by a personal computer. The display had a resolution of 1280(H) × 1024(V) pixels on a 21" (diagonal) screen. The refresh rate was 87 Hz. To avoid confusion, degrees of rotation were abbreviated as *DegRot*, whereas degrees of visual angle were abbreviated with the standard symbol (superscript circle). The target was a 0.5° filled gray circle on a black background that revolved smoothly around the screen center. To produce smooth continuous motion, the target position was updated with each screen refresh (every 11.5 ms). The target followed a circular orbit with a radius of 2, 3, 4, or 5°. The trajectory length was random within intervals of 315 ± 45, 405 ± 45, 495 ± 45, and 585 ± 45 DegRot. The initial orientation of the target was random as was its direction of rotation. The rotational velocity of the target was 90 or 120 DegRot/s. The target was the only stimulus presented on the screen.

Design. Each condition resulting from the factorial combination of direction of rotation (clockwise, counterclockwise), trajectory length (315, 405, 495, 585 DegRot), velocity (90, 120 DegRot/s), and radius (2, 3, 4, 5°) was presented once within a block of 64 trials. Three consecutive blocks were run for each eye movement instruction. Each eye movement condition

was run in a separate session, and the order of eye movement instruction ("Follow Target," "Look at Center") was balanced across participants.

Procedure

Participants sat in a dimly lit room 94 cm from the screen and initiated each trial by pressing a key. The target appeared and remained stationary for 0.5 s before it started to revolve. After the target vanished, observers were instructed to look at the final target position and to confirm their response by pressing another key. To reduce random jitter in the position signal, the mean eye position in a 50-ms window after the key press was taken as the judged final target position.

At the beginning of each session, observers were given oral instructions about where to direct their eyes. Either they were told to follow the target with their eyes (pursuit condition), or they were told to keep their eyes on the center of the screen (fixation condition). The experimenter monitored the eye movements on the master PC and gave corrective feedback if the observer deviated from the instructed eye movement instruction. This was rarely necessary. Observers received some practice trials drawn randomly from the experimental trials before each experimental session. None of the observers reported difficulties in following the instructions. During a session, the eye movement instruction remained the same and three blocks consisting of 64 experimental trials each were run. Within each block, the apparatus was calibrated every four trials. Sessions took place on different days, and a break was given after each block.

Results

Eye movement traces were visually inspected offline. On the basis of this inspection, a small number of trials had to be discarded because of faulty eye movement recording (1.1%). The remaining eye movement traces were transformed such that the actual VP was the origin of a new coordinate system (see Figures 1 and 2). The y axis of this new coordinate system corresponded to the tangent to a circle passing through the VP, and the x axis corresponded to a line passing through the VP and the center of the circle. Thus, the center of a circle with radius, r , was located at $x = -r$ and $y = 0$. The last part of the target's trajectory was located at $y \leq 0$; that is, the eye movement traces were rotated and flipped such that the trajectories were aligned in counterclockwise rotation. Deviations along the y axis are referred to as M-displacement and deviations along the x axis as O-displacement.

Figure 2 shows mean eye movement traces collapsed across eight observers in the pursuit condition from 200 ms before the target disappeared until 250 ms after the target disappeared. For each radius, rotational velocity, and eye movement condition, mean individual judgments of the final target position are shown. Table 2 shows the mean judged target position (M- and O-displacement) as a function of eye movement instruction, rotational velocity, and radius. Table 1 shows the mean eye position after oculomotor overshoot (M- and O-displacement) 250 ms after target offset as a function of eye movement instruction, rotational velocity, and radius. Furthermore, Table 1 shows the hypothetical target position if the target had revolved for another 250 ms after its actual offset.

Judged Final Position

The M- and O-displacement of the judged final position were analyzed separately. To evaluate effects of eye movement instruction, both combined analyses of variance (ANOVAs) and separate ANOVAs were run.

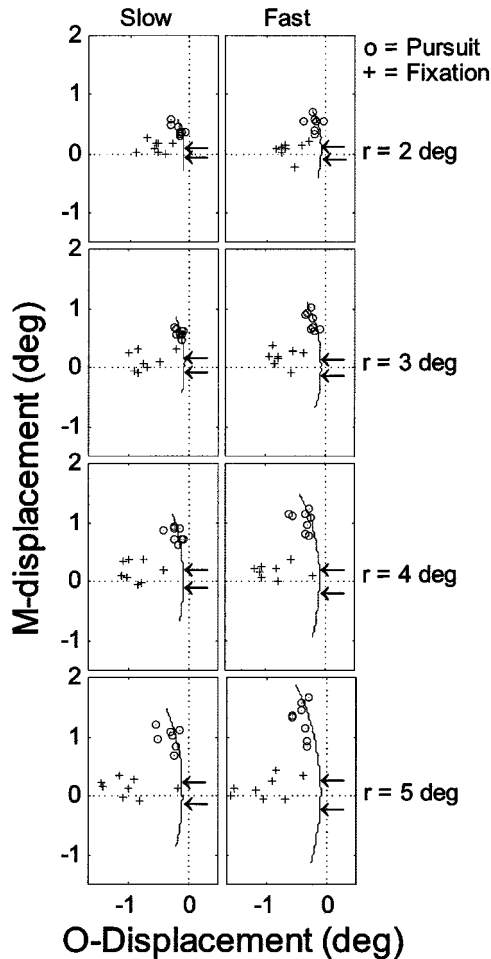


Figure 2. The average judged vanishing points (VPs) as a function of radius size, r (given in the figure's rows: target followed a circular orbit with a radius of 2, 3, 4, or 5°), and rotational velocity (given in the figure's columns: slow = 90, fast = 120 degrees of rotation per second). Unfilled circles indicate mean judgments of 8 observers when they followed the target with their eyes (pursuit condition). A clear dependence on both rotational velocity and radius size may be discerned. The crosses indicate mean judgments of 8 observers when they were looking at the screen center during stimulus presentation (fixation condition). Judgments depended on radius size only. Overall, judgments with pursuit of the target and center fixation formed two distinct distributions that showed virtually no overlap. The solid lines show the mean eye movement traces across 8 observers from 200 ms before to 250 ms after target offset. Eye movement traces were rotated and flipped such that the true VP was always at the origin of the coordinate system and the eyes revolved counterclockwise (see dashed box in Figure 1). The lower and upper arrows indicate the mean eye position at the time the target disappeared and 50 ms later, respectively. O-Displacement = displacement orthogonal to the tangent (i.e., along an axis passing through the true VP and the center of the orbit); M-Displacement = displacement along the tangent to the orbit; deg = degrees.

M-displacement. A three-way ANOVA (2 Instructions \times 2 Velocities \times 4 Radii) revealed that M-displacement was larger with smooth pursuit than with fixation, $F(1, 7) = 203.17$, $p < .0001$. M-displacement increased with velocity, $F(1, 7) = 29.51$, $p < .005$. The main effect of velocity was modified by eye movement instruction, $F(1, 7) = 23.37$, $p < .005$, indicating that

there was an increase in M-displacement with velocity when the observers were following the target but not when the eyes were directed at the screen center. Furthermore, M-displacement increased with radius, $F(3, 21) = 29.51$, $p < .001$. The main effect of radius was modified by eye movement instruction, $F(3, 21) = 45.77$, $p < .0001$, indicating that the increase was larger with pursuit than with fixation.

Separate two-way ANOVAs (2 Velocities \times 4 Radii) were run on the pursuit and fixation conditions. In the pursuit condition, an effect of velocity, $F(1, 7) = 40.42$, $p < .0004$, and radius, $F(3, 21) = 113.35$, $p < .0001$, was confirmed. The interaction of velocity and radius size approached significance, $F(3, 21) = 2.41$, $p = .0959$. The two-way ANOVA on the fixation condition did not reveal any significant effects ($ps > .13$).

Results of t tests showed that overall M-displacement was significantly (with Bonferroni corrected $\alpha = .05/2 = .025$) different from zero with smooth pursuit of the target (0.80°), $t(7) = 18.23$, $p < .0001$, and with fixation on the center (0.14°), $t(7) = 3.38$, $p < .02$.

O-displacement. Inspection of Table 2 shows that the variances in the fixation condition were larger than in the pursuit condition by a factor of 2–4. Thus, the combined ANOVA obviously violated the assumption of equal variances. The results are reported but should be treated with caution. A three-way ANOVA (2 Instructions \times 2 Velocities \times 4 Radii) showed that inward displacement was stronger when observers were fixating the screen center than when they were following the target, $F(1, 7) = 49.52$, $p < .0005$. Inward displacement increased both with increasing velocity, $F(1, 7) = 7.43$, $p < .05$, and with increasing radius, $F(3, 21) = 26.59$, $p < .0001$. Radius and instruction interacted, $F(3, 21) = 5.60$, $p < .01$, indicating that the effect of radius was stronger with fixation than with pursuit of the target. The interaction of velocity and instruction was marginally significant, $F(1, 7) = 5.26$, $p = .0556$, indicating that the effect of velocity was larger with pursuit than with fixation.

Separate two-way ANOVAs (2 Velocities \times 4 Radii) were run for the pursuit and fixation condition. In the pursuit condition, inward O-displacement increased with velocity, $F(1, 7) = 112.58$, $p < .0001$, and radius, $F(3, 21) = 23.81$, $p < .0001$. There was a significant interaction of velocity and radius, $F(3, 21) = 5.73$, $p < .01$, indicating that the effect of radius was stronger with the fast than with the slow velocity. In the fixation condition, inward O-displacement increased with radius, $F(3, 21) = 16.79$, $p < .0001$.

Results of t tests showed that overall O-displacement was significantly different from zero with pursuit of the target (-0.26°), $t(7) = -8.34$, $p = .0001$, and with fixation on the screen center (-0.81°), $t(7) = -8.97$, $p < .0001$.

Eye Position After Oculomotor Overshoot (Pursuit Condition)

The eye position 250 ms after target offset in the pursuit task is referred to as *eye position after oculomotor overshoot*. Around this time, the overshooting smooth pursuit eye movements stopped. Then, the eye typically moved again to judge the final target position. That is, the eye position after oculomotor overshoot always preceded the judged final target position. A time-locked analysis of the eye position data was possible only in the pursuit condition. Some 250 ms after target offset, observers in the fixa-

Table 2
M- and O-Displacement in Degrees of Visual Angle as a Function of Radius and Target Velocity

Radius	M-displacement				O-displacement			
	Eye position		Target position		Eye position		Target position	
	Slow	Fast	Slow	Fast	Slow	Fast	Slow	Fast
2°	0.57 ± 0.06	0.74 ± 0.05	0.62	0.81	-0.19 ± 0.04	-0.22 ± 0.06	-0.10	-0.17
3°	0.87 ± 0.03	1.10 ± 0.06	0.93	1.22	-0.23 ± 0.05	-0.32 ± 0.06	-0.15	-0.26
4°	1.14 ± 0.09	1.48 ± 0.08	1.24	1.63	-0.28 ± 0.06	-0.44 ± 0.06	-0.20	-0.35
5°	1.47 ± 0.09	1.88 ± 0.12	1.55	2.03	-0.37 ± 0.06	-0.54 ± 0.03	-0.24	-0.43

Note. Group means and between-subjects standard deviations are given in the format $M \pm SD$. The target followed a circular orbit with a radius of 2, 3, 4, or 5° and had either a slow velocity (90° of rotation per second) or a fast velocity (120° of rotation per second). Eye position after oculomotor overshoot is the position of the eye 250 ms after target offset in the pursuit condition. As can be seen from the standard deviations, all means were significantly different from zero (t tests, $ps < .0001$). Target position indicates the hypothetical displacement of the target if it had traveled on its trajectory for another 250 ms after it actually disappeared. The data show a close correspondence between where the target would have been 250 ms after target offset and where the eye was at the same time. M-displacement = displacement along the tangent (i.e., along an axis passing through the true vanishing point and the center of the orbit) to the orbit; O-displacement = displacement orthogonal to the tangent.

tion task were either still looking at the center or had already made a saccade to the final target position. In other words, performance in the fixation task was at leisure and did not allow for a time-locked analysis of the eye movement traces.

M-displacement. A two-way ANOVA (2 Velocities \times 4 Radii) confirmed that the M-displacement of the eye position after oculomotor overshoot increased with velocity, $F(1, 7) = 437.66$, $p < .0001$, and radius, $F(3, 21) = 1204.20$, $p < .0001$. The interaction of velocity and radius, $F(3, 21) = 19.16$, $p < .0001$, showed that the increase with radius was larger with the fast velocity.

O-displacement. A two-way ANOVA (2 Velocities \times 4 Radii) showed that inward O-displacement increased with velocity, $F(1, 7) = 129.41$, $p < .0001$, and radius, $F(3, 21) = 54.92$, $p < .0001$. The significant interaction of velocity and radius, $F(3, 21) = 9.02$, $p < .0005$, indicated that the effect of radius was larger with the fast than with the slow velocity.

Trial-by-Trial Correlation (Pursuit Condition)

The eye position after oculomotor overshoot and the judged final target position were correlated trial-by-trial for each observer. Note that the eye position after oculomotor overshoot was measured before the final target position was judged. All correlations were significant ($ps < .0001$). Individual correlations between M-displacement of the eye position after oculomotor overshoot and M-displacement of the judged final position varied between .55 and .77 ($M = .65$, Fisher's Z-transformed before averaging, and the mean was converted back). For O-displacement, individual correlations varied between .52 and .80 ($M = .63$). Furthermore, individual correlations were calculated between the euclidean distances of the eye position after oculomotor overshoot from the actual VP and the euclidean distance of the judged final target position from the actual VP. Correlations ranged between .56 and .80 ($M = .69$).

Discussion

The present experiment replicated some of the results reported by Hubbard (1996): M- and O-displacement increased with angular velocity and radius. However, this pattern was strongly modi-

fied by where the observers directed their eyes during target presentation. M- and O-displacement will be discussed in turn. When observers looked at the center of the orbit, M-displacement was much smaller than when observers were following the target with their eyes. Furthermore, M-displacement was not affected by radius size or rotational velocity with fixation on the screen center, whereas clear effects of both factors emerged with smooth pursuit of the target. The effects of radius and rotational velocity on the judged final position in the pursuit condition were mirrored by similar effects on the eye position 250 ms after target offset. Thus, both oculomotor overshoot and M-displacement increased with increasing radius size and rotational velocity. However, the deviation of the judged from the actual final target position was smaller than the eye position after oculomotor overshoot. This finding indicates that some compensation for the overshoot took place; however, the compensation was not complete. Mean compensation¹ was about 31% for M-displacement in the pursuit condition. Compensation after oculomotor overshoot may also explain why the interaction of rotational velocity and radius size, which was clearly present in the analysis of the eye position after oculomotor overshoot, did not reach significance in the analysis of the judged final position.

Furthermore, visual persistence of the target's image, which was measured to be about 50 ms (Kerzel, 2000), cannot explain the displacement of the judged final position in the pursuit condition. It is clear from Figure 2 that the eye position 50 ms after target offset differed substantially from the judged final position. Also, Figure 2 reveals that the eye lagged slightly behind the target: At target disappearance, the eye position (lower arrow in Figure 2) was not quite on the final target position. This lag is typical of smooth pursuit and is usually compensated for by catch-up saccades that bring the target back into the fovea (e.g., Carl & Gellman, 1987; Rottach et al., 1996). Furthermore, it is clear from Figure 2 that the judged final positions cluster densely around the

¹ Compensation, c , was defined with reference to the Euclidean distance between the eye position after oculomotor overshoot and the target's VP, $d(eye)$, and the Euclidean distance between the judged final target position and the target's actual VP, $d(judgment)$: $c = \frac{d(eye) - d(judgment)}{d(eye)}$.

oculomotor path. Therefore, one may conclude that observers' eyes went back some distance on their oculomotor path after overshooting the final target position, but they fell short of complete compensation. This conjecture is supported by the trial-by-trial correlation of eye position after oculomotor overshoot and judged final target position.

When the eyes were fixed on the screen center, eye movements did not overshoot the final target position, and consequently, no effects of radius and rotational velocity were observed. However, M-displacement with fixation was significantly different from zero. In contrast, previous studies did not find displacement in the direction of motion after target offset (Eagleman & Sejnowski, 2000; Kerzel, 2000; Whitney et al., 2000). The reasons for this discrepancy are unclear; however, it may be that the oculomotor system was stimulated by the moving target and engaged in anticipatory planning of eye movements, in particular because the eyes were directed at a void (i.e., there was no fixation point). Thus, the visual system may have anticipated where the target would be next and may have prepared an eye movement to that position. A possible test for such a hypothesis would be a comparison of relative judgments that do not involve motor planning and absolute judgments that have a certain motor component. Consistent with the notion of anticipatory control of eye movements, most of the previous studies that failed to report M-displacement with fixation used relative judgments (Eagleman & Sejnowski, 2000; Kerzel, 2000; Whitney et al., 2000). More important for the present study is the finding that overall M-displacement with fixation was five to six times smaller than with pursuit.

Similar to M-displacement, the pattern of O-displacement varied strongly as a function of eye movement instruction. O-displacement was larger with fixation on the screen center than with pursuit of the target. With fixation on the screen center, the target was localized toward the center, and this bias increased with radius but not with rotational velocity. Consistent with studies on the foveal bias, the target was localized toward the center by a fraction of 20–30% of the target's eccentricity. The bias toward the fovea was larger than in previous reports (10%, van der Heijden et al., 1999), which may be due to methodological differences, mainly the absence of a fixation point in the present study. With pursuit of the target, O-displacement was toward the center and increased with increases in radius size and rotational velocity. In addition, effects of radius size and rotational velocity interacted. The pattern of O-displacement with pursuit was mirrored by the position of the eye 250 ms after target offset. One may assume that observers compensated to some degree for the oculomotor overshoot by going back on their oculomotor path. Mean compensation was about 20% for O-displacement.

It remains to be explained why the interaction between rotational velocity and radius size reached significance in the ANOVA on O-displacement of the judged final position but failed to do so in the ANOVA on M-displacement. If the pattern of memory displacement was an exact mirror of the eye position after oculomotor overshoot, both effects should have been significant. This discrepancy may be explained by differences in how strongly changes in velocity affected increases in displacement with radius size. Inspection of the hypothetical target position (Table 1) shows that the effect of radius size on M-displacement differed by a factor of 1.3 between the slow and fast velocity (i.e., M-displacement increased by 0.31 vs. 0.41° per 1° radius size

increase), whereas the effect of radius size on O-displacement differed by a factor of 1.8 between the slow and fast velocities (i.e., O-displacement increased by 0.05 vs. 0.09° per 1° radius size increase). Another reason may be that the between-subjects variability was about twice as large with judgments of the final target position compared with the eye positions after oculomotor overshoot (cf. *SDs* in Tables 1 and 2). Whereas the eye position after oculomotor overshoot was fully determined by the machine-like properties of the human pursuit system, position judgments may have depended on participants' level of attention, effort, or strategies.

In sum, the results may be explained by two known oculomotor phenomena: First, the eyes overshoot the final position of a disappearing target, and the overshoot follows a preplanned trajectory. In the case of circular target motion, the eyes will be drawn toward the center. After pursuit offset, observers compensate to some degree for oculomotor overshoot such that the position of the eye at the end of the overshoot only partially determines the judged final position. Second, peripheral targets are localized toward the fovea. This explains O-displacement with fixation on the screen center and may also explain why compensation after oculomotor overshoot is incomplete: After oculomotor overshoot, the fovea is displaced in the direction of anticipated target motion, such that a bias toward the fovea results in displacement in the direction of motion.

In contrast, the present results are very hard to reconcile with the assumption of internalized centripetal force. First, there is no reason to expect the mental representation of acceleration toward the center (norm of vector \mathbf{a}) or representational momentum to vary as a function of gaze direction. However, M-displacement was larger with pursuit than with fixation, and O-displacement was larger with fixation than with pursuit. Second, the assumption that both rotational velocity and radius contribute to a cognitive analogue of $|\mathbf{a}|$ is challenged. On the one hand, rotational velocity did not affect M- or O-displacement when observers looked at the screen center. On the other hand, the effects (and interactions) of rotational velocity and radius size on M- and O-displacements were mirrored by a similar displacement of the eye position after oculomotor overshoot in the pursuit condition. This finding shows that the eye followed the predicted path of the target during oculomotor overshoot. The correlations between eye position and judged final target position in the pursuit condition show that oculomotor overshoot and position judgment were closely coupled.

Implications for Internalization

The main result of the present experiment was that memory displacement is not independent of what the observer is doing during stimulus presentation. Depending on the kind of eye movements induced by the display, different patterns of memory displacement result. Therefore, memory displacement is a function of the interaction between the observer's perceptual behavior and the display type. Of course, observers' perceptual behavior may be partially driven by memory and derived expectations about the future trajectory of the object; however, postperceptual cognitive processes are not causally responsible for memory displacement. For instance, M-displacement is reduced at predictable reversal points of the target's trajectory (Hubbard & Bharucha, 1988; Verfaillie & d'Ydewalle, 1991). This effect was attributed to

expectations distorting the remembered position. However, observers may also slow down the velocity of the eye movement when they expect a reversal of the target's trajectory (Kerzel, 2002a; Kerzel et al., 2001). In this case, expectations drive the eye movement, but the eye movement itself accounts for the displacement. Therefore, internalization of physical principles or effects of expectation do not seem to be adequate explanations for memory displacement with smooth stimulus motion. Rather, the distortions provide evidence for the view that properties of the observer that are unrelated to physical regularities, such as the choice of fixation point, oculomotor overshoot, and the foveal bias, cause distortions in memory.

On a more general note, the present study provides evidence for the view that observer action partially determines contents of our conscious experience (Hecht, 2001; Prinz, 1997). In this sense, memory displacement is a function of internal states of the observer but not so much of internalized states and properties of the external world. Thus, memory and observer action may be tightly coupled (see also Kerzel, 2001). Here, the eyes may be pulled toward the center for two action-related reasons: First, the oculomotor overshoot after smooth pursuit of circular motion is bent toward the center of rotation. Second, "lazy" participants may look at the center instead of following the target. Both deflections of the eye toward the center may result in inward displacement of the judged final target position.

Is There a Unified Theory of Memory Displacement?

As outlined in the introduction, it has been assumed that a number of physical regularities have been incorporated into the functional architecture of the mental system. Freyd's (1987) original work suggested that phenomenal aspects of physical momentum have been internalized. Later work extended this idea to gravity, friction, weight, and centripetal force (overview in Hubbard, 1995). More recent studies have challenged the hypothesis that phenomenal aspects of physical regularities cause memory displacement (Kerzel, 2000, 2002a; Kerzel et al., 2001). It was proposed that oculomotor behavior in combination with some known distortions of visual space explains the pattern of displacement. For instance, forward displacement may be due to oculomotor overshoot, not to representational momentum. The question arises whether oculomotor behavior may offer a unified theory of memory displacement and thereby fully replace higher level cognitive mechanisms, such as internalization. The answer is no for two reasons:

First, there are reports of memory displacement in the absence of motion. For instance, observers' memory for static pictures implying motion was shifted in the direction of anticipated motion (Freyd, 1983; Freyd, Pantzer, & Cheng, 1988): Freyd (1983) presented target pictures of creatures or objects in the middle of an event (e.g., a person in the middle of jumping down a wall) and asked observers to memorize the picture. When asked to judge test pictures as "same" or "different" that depicted the same action slightly before or after the target snapshot, observers found it more difficult to reject test pictures as different from the target picture that followed in time. It is unlikely that eye movements contributed to this error because smooth pursuit eye movements do not occur in the absence of motion (e.g., Yasui & Young, 1975). It is more plausible that mental extrapolation of the dynamic event sequence accounted for forward memory displacement.

Second, forward displacement also occurs with implied motion (e.g., Freyd & Finke, 1984; Freyd & Johnson, 1987). In the present study, target motion was smooth. That is, the target position was updated with every screen refresh (less than 12 ms) such that the temporal resolution of the visual system prevented the detection of discrete position steps between successive screen refresh cycles. Smooth motion is an effective stimulus for smooth pursuit eye movements (e.g., Yasui & Young, 1975). In contrast, implied motion impairs smooth pursuit (e.g., Churchland & Lisberger, 2000) because the temporal and spatial differences between successive position steps are too large: Typically, the target is presented for 250 ms at the same position, and successive target presentations are separated by 250-ms blank intervals. Therefore, oculomotor overshoot after smooth pursuit may not explain forward displacement with implied motion. In fact, a recent study measured eye movements in an implied motion display and found that forward displacement occurred in the absence of systematic eye movements (Kerzel, in press).

In sum, there may not be a single mechanism underlying memory displacement. With smooth stimulus motion, smooth pursuit eye movements rather than internalized physical regularities account for the memory displacement: Presently, the hypothesis of internalized centripetal force was not supported by the data. Previous studies showed that effects attributed to internalized momentum and friction may be at least partially perceptual (Kerzel, 2000, 2002a; Kerzel et al., 2001). In contrast, high-level cognitive factors distort memory for static pictures of dynamic events or implied motion stimuli. In these cases, mental extrapolation of event sequences may bias judgments in the direction of anticipated motion. Thus, previous research has overestimated the role of internalized physical regularities in memory displacement. The present research corrects this overstatement and shows that perceptual mechanisms may account for some of the data. The price to pay is conceptual parsimony: The internalization of physical regularities as the single source of memory biases has to be replaced by a rather complex interaction of display type, perceptual behavior, and cognitive activity.

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