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Cognitive representation of linear motion: Possible direction and gravity effects in judged displacement

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The judged vanishing point of a target undergoing apparent motion in a horizontal, vertical, or oblique direction was examined. In Experiment 1, subjects indicated the vanishing point by positioning a crosshair. Judged vanishing point was displaced forward in the direction of motion, with the magnitude of displacement being largest for horizontal motion, intermediate for oblique motion, and smallest for vertical motion. In addition, the magnitude of displacement increased with faster apparent velocities. In Experiment 2, subjects judged whether a stationary probe presented after the moving target vanished was at the same location where the moving target vanished. Probes were located along the axis of motion, and probes located beyond the vanishing point evidenced a higher probability of a *same* response than did probes behind the vanishing point. In Experiment 3, subjects judged whether a stationary probe presented after the moving target vanished was located on a straight-line extension of the path of motion of the moving target. Probes below the path of motion evidenced a higher probability of a *same* response than did probes above the path of motion for horizontal and ascending oblique motion; probes above the path of motion evidenced a higher probability for a *same* response than did probes below the path of motion for descending oblique motion. Overall, the pattern of results suggests that the magnitude of displacement increases as proximity to a horizontal axis increases, and that in some conditions there may be a component analogous to a gravitational influence incorporated into the mental representation.

When an apparently moving target vanishes without warning, the location at which it is judged to have vanished is systematically displaced from the true vanishing point as a function in part of the target's velocity and direction of motion. In a previous study (Hubbard & Bharucha, 1988), subjects saw apparently moving circular targets traveling either horizontally or vertically across a CRT screen; these targets would vanish without warning. After the targets vanished, the subjects indicated the vanishing point by positioning a crosshair on the screen. In the absence of other stimuli, the judged vanishing point was displaced forward along the axis of motion; this was referred to as *M displacement*. The amount of M displacement was related to both the velocity and the direction of motion such that faster velocities resulted in larger magnitudes of M displacement, and horizontal directions of motion resulted in larger magnitudes of M displacement than did vertical directions of travel. Targets traveling horizontally were also found to be displaced downward along the axis orthogonal to motion; this was referred to as *O displacement*.

Given the larger M displacement found with horizontal motion, it is of interest to examine performance for directions intermediate to the horizontal and vertical axes. Three predictions are possible: (1) Displacements in oblique or diagonal directions might be intermediate in magnitude between displacements in horizontal and vertical directions. Thus, the closer to the horizontal axis the path of motion is, the greater the displacement. (2) Displacements in oblique directions might be greater in magnitude than displacements in horizontal and vertical directions. Thus, the closer to a cardinal axis the path of motion is, the smaller the displacement. Perceptual research in a variety of settings has shown decrements in performance when stimuli are oriented at oblique angles (for review, see Appelle, 1972). For example, both resolution (Berkley, Kitterle, & Watkins, 1975; Bowker & Mandler, 1981) and vernier (Corwin, Moskowitz-Cook, & Green, 1977) acuity are impaired when the stimuli are oriented at angles intermediate to the horizontal and vertical axes. (3) Displacements in oblique directions might be smaller in magnitude than displacements in horizontal and vertical directions. Thus, the closer to a cardinal axis the path of motion is, the greater the displacement. Such a pattern might be predicted if the processing pathways for motion along the cardinal axes were independent of or prior

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to the processing pathways for motion along oblique axes; by virtue of their primacy, extrapolations along cardinal axes would thus be facilitated.

The displacement phenomenon is analogous, and may even be identical in its underlying mechanisms, to a phenomenon referred to as *representational momentum* by Freyd and Finke (1984). In Freyd and Finke's basic paradigm, a rectangle is presented in a series of three differing orientations. A fourth rectangle is then shown and the subject is asked if the orientation of the fourth rectangle is the same as that of the third rectangle of the preceding series. The fourth rectangle is rotated slightly backward of the true orientation (backward distractor), at the true orientation (same), or rotated slightly forward of the true orientation (forward distractor) of the third rectangle. When the presentation order of the first three rectangles was such as to suggest implied rotation in a constant direction, subjects were more likely to judge that forward distractors were at the true final orientation than they were to judge that backward distractors or same rectangles were at the true final orientation. In essence, the judged orientation of the last rectangle was displaced forward in the direction of implied rotation.

Finke and Freyd (1985) and Kelly and Freyd (1987) proposed that the representational momentum phenomenon is due to a simulation or internalization of the properties of momentum by the human visual system (although Freyd, 1987, has since suggested that representational momentum is a property of a mental representation system that is in itself dynamic). Kelly and Freyd suggested that the implied motion of an object causes an observer to mentally extrapolate the object forward into a future position. The strength of this extrapolation is determined by the strength of the momentum associated with the implied motion. Cognitive effort is needed to keep the extrapolation from continuing; this cognitive effort parallels the physical effort that is needed to stop a physical object from continuing along its path of motion in the absence of any other forces.

If the visual system extrapolates one element of real motion—momentum—it is possible that other elements are also incorporated into the mental representation. What other types of elements might be incorporated? Shepard (1984) proposed that mental representations incorporate constraints reflecting some of the invariances found in the world. One element that is both pervasive and invariant (although not explicitly addressed by Shepard) is the influence of gravity, so elements of motion due to gravity might be incorporated into mental representation. Freyd, Pantzer, and Cheng (1988) showed subjects a drawing that portrayed a flowerpot as either suspended from a hook or resting on a table. The subjects were then shown a second drawing of the flowerpot in which the hook or table was removed, and then judged whether the redrawn flowerpot was at the same location as the original flowerpot. The subjects were more likely to give a judgment of *same* to a redrawn flowerpot that was lower than the original height than to a redrawn flowerpot that was higher than the original height. This finding is consistent with the notion that an element corresponding to a gravitational effect is incorporated into the mental representation; that is, an unsupported physical object would be displaced downward (fall). A gravity component of the mental representation may also underlie some of the findings of Hubbard and Bharucha (1988)—namely that (1) targets moving horizontally were displaced slightly downward from the axis of motion, as if they were falling or losing altitude as they were extrapolated forward, and (2) targets traveling from top to bottom showed larger forward displacements than did targets traveling from bottom to top, consistent with the idea that falling objects accelerate and rising objects decelerate.

EXPERIMENT 1

This experiment is a partial replication and extension of Experiments 1 and 2 of Hubbard and Bharucha (1988). In those experiments, subjects were presented with apparent linear motion in horizontal and vertical directions. The subjects were instructed to pinpoint the vanishing point of the target by positioning a crosshair on the screen, and the distance between the true vanishing point and the indicated vanishing point was measured. In the current experiment, this method is replicated and extended by including four directions of oblique motion and by limiting the viewing area to a circular shape. By including oblique motion, the magnitude of displacement along both cardinal and oblique axes may be compared. In addition, the displacement pattern observed for obliquely moving targets may shed light on the question of gravity component in the mental representation, since both obliquely ascending and descending movements would be expected to be influenced by gravity in clearly predictable ways.

Method

Subjects. The subjects in all experiments consisted of Franklin and Marshall College undergraduates recruited from introductory and intermediate-level psychology classes. They received either partial course credit or a small cash payment in return for their participation. No subject participated in more than one experiment, and all subjects were naive to the hypotheses until after their data had been collected. Fifteen subjects participated in the current experiment.

Apparatus. The stimuli were displayed upon and data collected by an Apple Macintosh II computer equipped with a standard Apple monochrome monitor. A medium-gray cardboard sheet with a circular cutout was placed over the screen. The circular cutout, employed so that equal distances for each direction would be obtained, was centered on the middle of the screen. The diameter of the circle matched the height of the screen. The subjects were allowed to adjust the viewing distance to achieve maximum comfort and confidence in their responses.

Stimuli. The target stimulus was a filled (black) circle presented on a white background. The target was 20 pixels in diameter (subtending an estimated visual angle of approximately 50 min). The diameter of the circular area of the screen seen through the cutout was approximately 460 pixels (estimated visual angle of 19.2°).

The target emerged from behind the edge of the screen and moved at a constant velocity toward the opposite side of the screen. The target traveled in one of eight directions: left to right (LR), right to left (RL), top to bottom (TB), bottom to top (BT), upper left to lower right (ULLR), lower right to upper left (LRUL), upper right to lower left (URLL), and lower left to upper right (LLUR). The target vanished at one of five locations evenly spaced across the screen. The vanishing points were separated by approximately 2° along the path motion for LR, RL, TB, and BT (48 pixels along either the *x*- or the *y*-axis), and by approximately 2.1° along the path of motion for ULLR, LRUL, URLL, and LLUR (36 pixels along the *x*-axis). Locations 1 and 2 were between the side of the screen where the target emerged and the midpoint of the screen, Location 3 was near the approximate midpoint, and Locations 4 and 5 were between the side opposite where the target emerged and the midpoint. Target velocity was controlled by varying the separation between successive presentations of the target. Three velocities were used, corresponding to shifts 1, 2, and 3 pixels per presentation. The pixels were square in shape, so shifts of an equal number of pixels either horizontally or vertically resulted in shifts of equal distance. These shift sizes resulted in approximate apparent velocities of 4.2°/sec, 8.3°/sec, and 12.5°/sec for horizontal and vertical motion, and 5.9°/sec, 11.8°/sec, and 17.7°/sec for oblique motion. Each subject received 600 trials (8 directions × 3 velocities × 5 vanishing points × 5 replications) in a different random order.

Procedure. The subjects initiated each trial by pressing a designated key. They were first given a practice session consisting of 12 trials that had been randomly selected from the experimental trials. On each trial, the moving target emerged from behind the cutout and crossed toward the opposite side of the screen. The subjects were instructed to watch the target. Somewhere along its path, the target vanished. The cursor, in the form of a crosshair, then appeared near the center of the screen and the subjects positioned the center of the crosshair over where the center of the target was when the target disappeared. The cursor was positioned via movement of a computer mouse; the subjects were instructed to be as accurate as possible in placement of the cursor, and were allowed to take as much time as they needed. When positioning was complete, the subject clicked a button on the mouse in order to record the screen coordinates of the crosshair. The subject then initiated the next trial.

Results and Discussion

The differences between the true vanishing point and the judged vanishing point along the *x*- and *y*-axes were calculated; this difference is referred to as *displacement*. For the horizontal directions (LR and RL), displacement along the axis of motion (*x*-axis) is referred to as M displacement and displacement along the axis orthogonal to motion (*y*-axis) is referred to as O displacement. For the vertical directions (TB and BT), displacement along the *y*-axis is referred to as M displacement and displacement along the *x*-axis is referred to as O displacement. For the directions (ULLR, LRUL, URLL, and LLUR), the path of motion does not correspond to either the *x*- or the *y*-axis; an estimate of displacement based on both X and Y displacement for those directions (referred to as *V displacement*) will be explained below. The alpha level required for significance in all statistical analyses was .01.

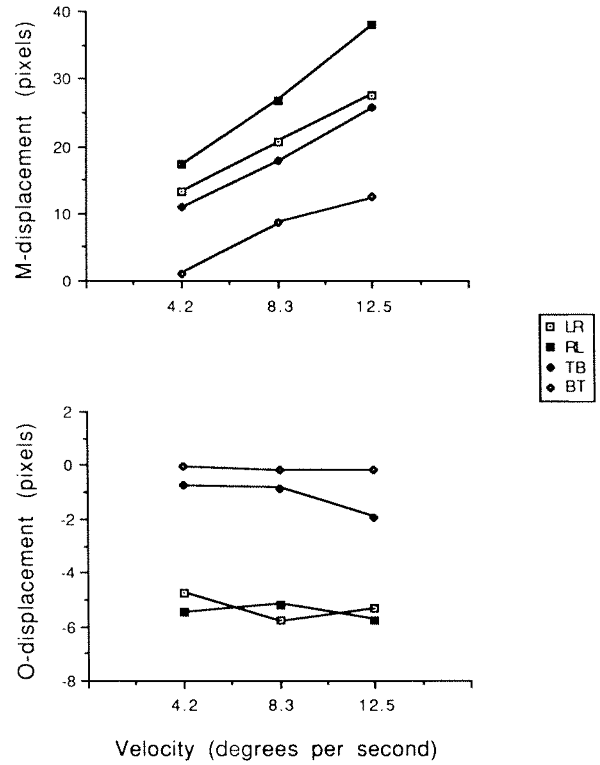

Figure 1. Displacement along the axis of motion (M displacement, upper panel) and the axis orthogonal to motion (O displacement, lower panel) as a function of target velocity in Experiment 1.

M displacement. As shown in the top panel of Figure 1, all of the mean M displacement scores were positive; that is, judged vanishing points were, on the average, located beyond the true vanishing points. The M displacement scores were analyzed using a 4 (directions) × 3 (velocities) repeated measures analysis of variance (ANOVA). The effect of direction was significant [*F*(3,42) = 23.04, *MS*$_e$ = 135.64]. Planned comparisons revealed that the horizontal directions resulted in more forward displacement than did the vertical directions [*F*(1,14) = 105.72, *MS*$_e$ = 53.12]. In addition, RL resulted in more displacement than did LR [*F*(1,14) = 11.99, *MS*$_e$ = 94.05], and TB resulted in more forward displacement than did BT [*F*(1,14) = 10.13, *MS*$_e$ = 295.74]. There was a significant effect of apparent velocity on M displacement [*F*(2,28) = 56.18, *MS*$_e$ = 62.42]. As shown in the top panel of Figure 1, faster velocities lead to larger forward M displacement. The slope of BT motion is significantly less than that for the other directions, as shown by a significant direction × velocity interaction [*F*(6,84) = 3.16, *MS*$_e$ = 20.10]. This pattern of results replicates precisely the effects of direction and velocity on M displacement observed in Experiments 1 and 2 of Hubbard and Bharucha (1988)—namely, that (1) faster apparent velocities lead to larger amounts of forward M displacement, (2) horizontal directions lead to larger amounts of forward M displacement than do vertical directions, and (3) RL leads to larger forward M displacement than does LR, and TB leads to larger forward M displacement than does BT. Furthermore, the current experiment utilized the circular cutout, so these effects cannot be attributed to any confounds of screen dimension and direction.

O displacement. The O displacement scores were analyzed with a 4 (directions) × 3 (velocities) repeated measures ANOVA. The effect of direction was significant [$F(3,42) = 13.73$, $MS_e = 24.99$]. Planned comparisons showed that horizontal directions resulted in larger magnitudes of O displacement than did vertical directions [$F(1,14) = 14.57$, $MS_e = 69.01$]. Furthermore, as shown in the bottom panel of Figure 1, horizontal directions show displacement *below* the axis of motion. The effect of velocity [$F(2,28) = 1.96$, $MS_e = 2.073$] and the velocity × direction interaction [$F(6,84) = 1.14$, $MS_e = 2.166$] did not attain significance. Again, this pattern of results replicates the downward O displacements found in our previous work.

X and Y displacement. Although neither the *x*- nor the *y*-axis represents the true path of motion for targets traveling in an oblique direction, a comparison of displacements on these axes is of interest because the idea of a gravity component discussed earlier makes specific predictions about the relative magnitudes of the X and Y displacements. Specifically, if a gravity component is manifested in the responses, then Y displacements should be less than X displacements for ascending targets, and Y displacements should be greater than X displacements for descending targets. The logic is as follows: Oblique targets travel at a 45° angle with regard to both the *x*- and the *y*-axes. If displacement is solely along the path of motion, then the X and Y components should be approximately equal. If displacement deviates from the path of motion, then inequalities between the X and Y components will appear. The direction of inequality consistent with a downward gravitational influence is a smaller Y for ascending motion and a larger Y for descending motion.

The X and Y displacements were entered in a 4 (oblique directions) × 3 (velocities) × 2 (axes) repeated measures ANOVA. The effect of axis was highly significant [$F(1,14) = 88.58$, $MS_e = 49.71$], with the *x*-axis showing larger overall magnitudes of displacement than the *y*-axis. The axis factor also interacted significantly with direction [$F(3,42) = 14.00$, $MS_e = 81.71$], with velocity [$F(2,28) = 7.84$, $MS_e = 8.14$], and with direction × velocity [$F(6,84) = 4.18$, $MS_e = 5.18$]. As shown in Figure 2, the descending oblique directions have X and Y displacements of nearly equal magnitudes. For the ascending oblique directions, however, the Y displacements are significantly smaller than the X displacements. The pattern of X and Y displacements for ascending oblique directions, larger M displacement for TB than BT, and negative O displacement for LR and RL are all consistent with the idea of a gravity component to the mental representation. The relative equality of X and Y displacements for descending oblique directions does not, however, initially appear consistent with the idea of a gravity component, but this will be addressed in more detail below.

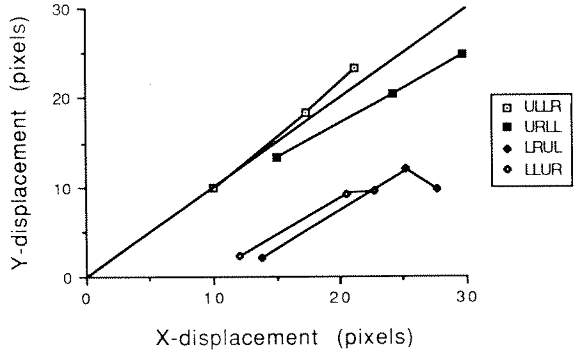

Figure 2. Displacement along the *x*- and *y*-axes for oblique motion in Experiment 1. The solid diagonal line indicates the function that would be obtained if the displacements along both axes were of equal magnitudes.

V displacement. To determine if any type of oblique effect occurs in the judged displacement, it is desirable to have a metric by which to compare displacements of horizontal and vertical directions directly with those of the oblique directions. However, direct comparison of the X and Y components of each direction of motion is not meaningful in evaluating an oblique effect for two reasons: (1) In one case, these axes lie along the axis of motion and the orthogonal axis, and in the other case they lie between the axis of motion and the orthogonal axis. Thus, axis role is confounded with direction. (2) Overall, the apparent velocities for oblique motion are faster than for horizontal and vertical motion. Although the number of pixels shifted along each axis was the same (e.g., horizontal, vertical, and oblique motion all involved increments of 1, 2, or 3 pixels along the *x*-axis and/or the *y*-axis between successive presentations of the target), a target traveling an oblique path actually traverses a greater distance (length of *x* or *y* multiplied by the square root of 2), thus resulting in a faster apparent velocity.

Comparison of the magnitudes of displacement in oblique motion with the magnitudes of displacement in horizontal and vertical motion therefore involves calculation and comparison of the length of the actual displacement vector. The measure, called V displacement, is calculated by solving for the square root of the sum of the squares of the X and Y displacements. V displacements for each direction and velocity are shown in Figure 3. It is clear that faster velocities lead to greater magnitudes of V displacement, and when the data from all conditions are combined, the velocity effect is highly significant [$F(2,28) = 59.87$, $MS_e = 111.58$]. The relatively lower slope for BT is reflected in a significant direction × velocity interaction [$F(14,196) = 4.91$, $MS_e = 16.72$]. To examine the effect of direction on V displacement by including all of the data in the ANOVA would be misleading, since the oblique directions possess a faster apparent velocity than do the horizontal and vertical directions

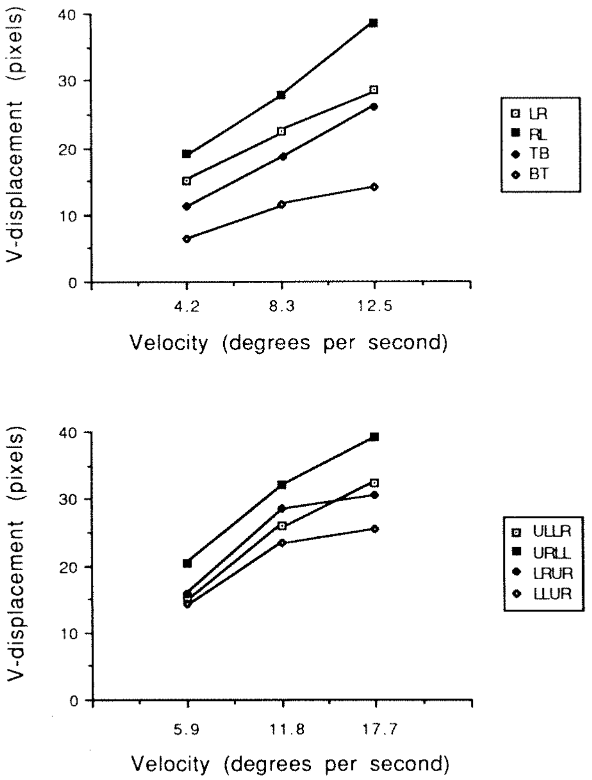

Figure 3. The vector of total displacement (V displacement) as a function of target velocity for the horizontal and vertical directions (upper panel) and for the oblique directions (lower panel) in Experiment 1.

(as explained above). Differences between directions may be found simply as a result of this different velocity and not due to any effects of direction per se. What is necessary is to examine a subset of the data chosen so that the apparent velocities of each direction are relatively equal. Therefore, the effect of direction was examined by comparing the V displacement scores from the fast velocity for LR, RL, TB, and BT with the V displacement scores from the medium velocity for ULLR, LRUL, URLL, and LLUR directions using a one-factor (direction) repeated measures ANOVA. There was a significant effect of direction on V displacement [$F(1,14) = 13.50$, $MS_e = 56.58$]. Planned comparisons showed that oblique directions resulted in smaller magnitudes of forward V displacement than did horizontal directions [$F(1,14) = 17.48$, $MS_e = 44.20$], and larger magnitudes of V displacement than did vertical directions [$F(1,14) = 36.33$, $MS_e = 30.42$].

It appears that the previous results on displacement for horizontal and vertical motion can be extended to include oblique motion. The representation of the target is displaced in the direction of motion, and faster apparent velocities lead to larger magnitudes of displacement. The magnitude of displacement for oblique motion is intermediate between those of horizontal and vertical motion. The lowered performance levels typical of many perceptual tasks using obliquely oriented stimuli does not seem to generalize to the displacement phenomenon; rather, the magnitude of the effect seems determined in part by the proximity of the path of motion to the horizontal axis. Specifically, the closer to the horizontal axis the path of motion is, the greater the total displacement.

The evidence for a gravity component in the mental representation of the motion is not so clear, however. Ascending targets show clear evidence of a gravity effect; the representation was displaced forward less on the y-axis than on the x-axis. Descending targets, however, do not show clear evidence of a gravity effect; the displacement on the y-axis was relatively equal to that on the x-axis. This apparent incongruity can be explained, however, if the gravity component operated simultaneously with a horizontal motion effect. Given that X displacement is normally larger than Y displacement, any decrease in Y displacement due to gravity in ascending motion would only accentuate a difference that already existed. Descending motion would predict that Y displacement would be larger than X displacement, but since Y displacement is initially smaller than X displacement, Y displacement can increase somewhat in magnitude without becoming larger than X displacement. The fact that, for descending motion, X and Y displacements were relatively equal may result from the increase in Y displacement caused by gravity. The failure to obtain the predicted difference between X and Y displacements for descending oblique motion may thus have resulted from the fact that Y displacement was smaller than X displacement to begin with. In essence, Y displacement increased as predicted, but since the magnitude of the X displacement was already so large, the total Y displacement did not surpass it. Inspection of Figure 2 supports this interpretation, as it clearly shows larger Y displacements for descending motion than for ascending motion (as would be predicted by gravity), but the relatively large X displacements for both ascending and descending oblique motion.

EXPERIMENT 2

It is possible that the displacement patterns observed in Experiment 1 resulted from idiosyncracies specific to the cursor-positioning paradigm and not from a robust tendency of the subjects' mental representations to extrapolate to a future position of the target. If the displacement phenomenon is valid, then it should be possible to observe displacement effects using a different paradigm. In Experiment 2, the same target motion was presented as was used in Experiment 1, and subjects judged whether a subsequently presented stationary probe was at the location at which the target vanished or at a different location. Probes were located along the axis of motion either beyond or behind the true vanishing point. If previous displacement findings are valid, then subjects should be more likely to judge *same* for probes located beyond the vanishing point than for targets located behind the vanishing point. This type of forced-choice task is similar to the measures used by Freyd and Finke (1984) in their studies of representational momentum.

Method

Subjects. The subjects consisted of 15 undergraduate drawn from the same pool used in the previous experiment.

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

Stimuli. The moving target was the same as in Experiment 1. There were two vanishing points for each direction. For horizontal and vertical directions, the vanishing points were located along the axis of motion, 48 pixels (2°) to either side of the midpoint of the screen; for the oblique directions, the vanishing points were located along the *x*-axis, 36 pixels (1.5° along the *x*- or *y*-axis, 2.1° along the path of motion) to either side of the midpoint of the screen. Thus, all vanishing points lay along a circle roughly concentric with the midpoint of the screen. The vanishing point closest to the side of the screen where the target entered was referred to as the *near point*; the vanishing point on the side opposite from where the target entered was referred to as the *far point*. After the target vanished, a stationary probe of the same shape, size, and color as the moving target appeared on the screen. For LR, RL, TB, and BT, the center of the probe was located along the axis of motion of the moving target, and was located 12 pixels (30 min) or 6 pixels (15 min) behind the vanishing point, at the vanishing point, or 6 or 12 pixels beyond the vanishing point. For ULLR, LRUL, URLL, and LLUR, the center of the probe was located along the axis of motion, and was located 12 pixels (42 min along the oblique axis) or 6 pixels (21 min along the oblique axis) behind the *x*-coordinate of the vanishing point, at the vanishing point, or 6 or 12 pixels beyond the vanishing point. One target velocity, corresponding to a shift of 2 pixels per presentation (equivalent to the medium velocity in Experiment 1), was used. Each subject received 800 trials (8 directions × 2 vanishing points × 5 probe locations × 10 replications) in a different random order.

Procedure. The procedure was the same as in Experiment 1, with the following exceptions. One second after the moving target vanished, a probe of the same shape, size, and color as the moving target appeared on the screen. The subjects judged whether the probe was at the vanishing point; they were instructed to be as accurate as possible and were allowed as much time as they needed. The probe remained on the screen until the subject responded. The subjects were told that it was possible that there would be more *sames* than *differents*, equal numbers of *sames* and *differents*, or fewer *sames* than *differents*. They then pushed either a *same* or a *different* key to indicate their response.

Results and Discussion

There were five possible locations around each vanishing point at which the probe could have appeared, and these locations were numbered consecutively 1-5. Locations 1 and 2 were behind the vanishing point, Location 3 was centered on the vanishing point, and Locations 4 and 5 were beyond the vanishing point. The probability of a *same* judgment as a function of probe location is shown in Figure 4. Were subjects responding accurately, there would have been 0% *same* responses on Locations 1, 2,

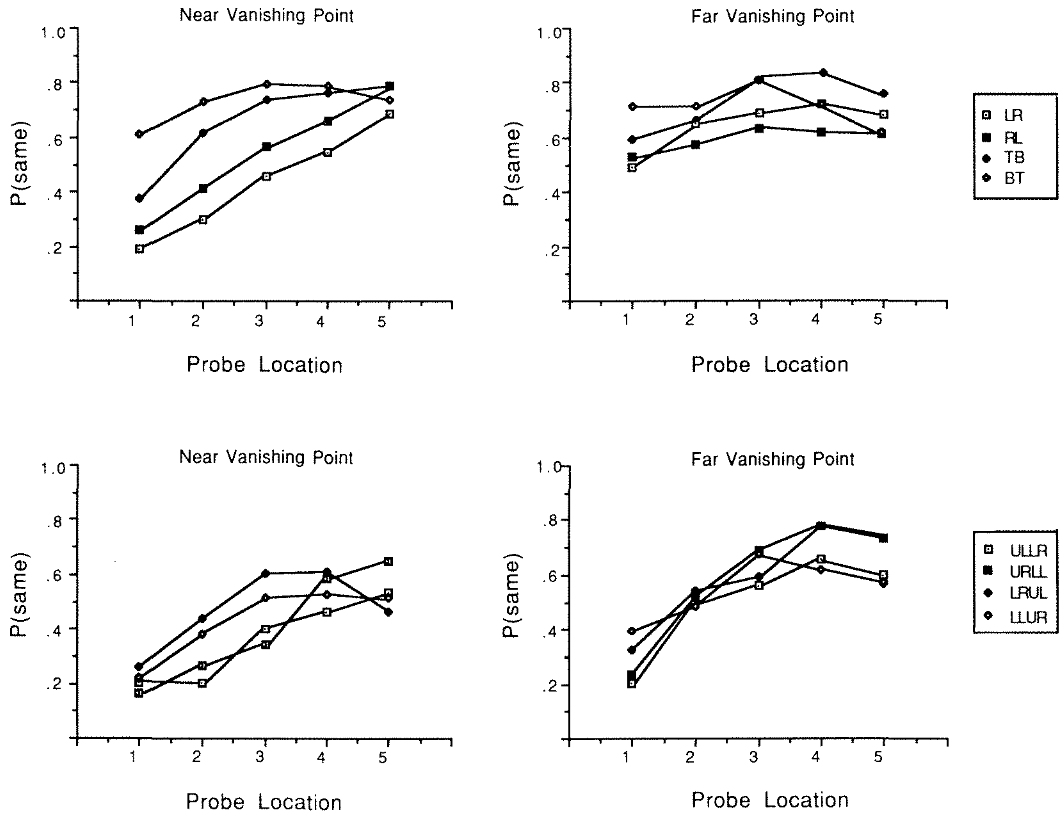

Figure 4. Probability of a *same* response as a function of probe location in Experiment 2. The upper panels display probability for the horizontal and vertical directions, and the lower panels display probability for the oblique directions. The left panels display probability for the near vanishing point, and the right panels display probability for the far vanishing point.

4, and 5, and 100% *same* responses on Location 3. The alpha level required for significance in all statistical analyses was .01.

The choice probabilities were analyzed using an 8 (directions) × 2 (vanishing points) × 5 (probe locations) repeated measures ANOVA. As shown in Figure 4, probe location significantly influenced the probability of a *same* response [$F(4,56) = 36.12$, $MS_e = .11$], but interpretation of this effect must be tempered by consideration of significant interactions of probe location with direction [$F(28,392) = 3.64$, $MS_e = .03$], with vanishing point [$F(4,56) = 3.11$, $MS_e = .09$ ($.01 < p < .05$)], and with direction × vanishing point [$F(28,392) = 2.73$, $MS_e = .02$]. In general, probes beyond the vanishing point were more likely to be judged *same* than were probes behind the vanishing point. Pairwise comparisons using Newman-Keuls tests ($p < .01$) showed that the probability of *same* responses of Locations 4 and 5 were significantly greater than the probability of *same* responses of Locations 1 and 2. This is precisely what we would expect if the mental representation of the target is displaced forward.

The amount of distance the target traveled influenced the probability of a *same* response, as shown by a significant effect of vanishing point [$F(1,14) = 18.57$, $MS_e = .174$], such that probes at the far vanishing point demonstrated a higher probability of a *same* response than did probes at the near vanishing point. The additional viewing time afforded by the far vanishing point appears to have somewhat leveled out the function relating the probability of a *same* response to probe position for LR, RL, and TB, but does not seem to have had as much of an effect on BT and the oblique directions, as indicated by a significant vanishing point × direction interaction [$F(7,98) = 4.62$, $MS_e = .05$].

The direction of target motion affected the probability of a *same* judgment [$F(7,98) = 12.14$, $MS_e = .13$]. Planned comparisons showed that the probability of responding *same* was greater for horizontal and vertical directions than for oblique directions [$F(1,14) = 60.60$, $MS_e = .11$], consistent with the slightly greater spatial separations of probe location in oblique directions, but despite the fact that apparent velocity was actually slightly faster for oblique than for horizontal and vertical directions. Horizontal motion resulted in a higher probability of a *same* response than did oblique motion [$F(1,14) = 15.91$, $MS_e = .07$], which might be considered analogous to the larger V displacements for horizontal than for oblique motion found in Experiment 1. Vertical motion led to a higher probability of a *same* response than did either horizontal [$F(1,14) = 27.94$, $MS_e = .13$] or oblique [$F(1,14) = 61.85$, $MS_e = .17$] motion. The larger proportion of *same* responses for vertical motion relative to either horizontal or oblique motion is puzzling, but may have occurred because the probe appeared closer to the edge of the visual periphery for motion in the vertical directions than for motion in either the horizontal or the oblique directions. Experiment 1 did not consider the proximity of the stimulus elements to the periphery, as the subjects had no reason to expect a stimulus to occur away from the true vanishing point. In Experiment 2, however, the possibility of a stimulus (probe) some distance away from the presumed fixation or foveal point (true vanishing point) existed, so the acuity differences between fixation and periphery become more important. According to this line of thought, the poorer performance—that is, the higher overall proportion of *same* responses for vertical than for horizontal motion—arose because of lower acuity due to the closer proximity of the probes to the edge of the periphery in the vertical motion condition. There were no differences between LR and RL [$F(1,14) = .17$, $MS_e = .21$], or between TB and BT [$F(1,14) = .60$, $MS_e = .10$].

Overall, the results of Experiment 2 support the idea that the representation of the target was displaced in the direction of motion. No difference was found between LR and RL or between TB and BT, replicating a previous forced-choice experiment (Hubbard & Bharucha, 1988, Experiment 3) in which probe locations were limited to either a target at the vanishing point or a target displaced forward. The consistent finding of an asymmetry between LR and RL and between TB and BT in the cursor-positioning paradigm, and the consistent failure to obtain those asymmetries with a forced-choice paradigm, may result from (1) idiosyncracies of the cursor-positioning paradigm and not from any aspects of the mental representation per se, or (2) relative insensitivity of the forced-choice paradigm to this effect (perhaps due to large spacing of the choice alternatives).

EXPERIMENT 3

Experiment 1 provided evidence that, at least for some directions, the mental representation of the target could be displaced in a direction other than that of motion (see also Bharucha & Hubbard, 1989). Specifically, targets traveling a horizontal path were also displaced downward, and targets ascending an oblique path were displaced less along the y-axis than the x-axis. The current experiment examines if these patterns are also observed in a mental extrapolation task. Finke and Shyi (1988) have demonstrated that forward displacements occur in an extrapolation task but that the magnitudes of the displacements are much weaker than in a memory task, so it is of interest whether displacements in other (nonforward) directions can also be found in an extrapolation task. In the current experiment, each probe was located beyond the vanishing point and subjects judged whether that probe was on a straight-line extension of the moving target's path of motion. Forced-choice options aligned along the axis of gravity (the y-axis) for horizontal and oblique directions were used so that the gravity effect mentioned earlier could be further examined, and forced-choice options along the orthogonal axis for the vertical directions (the x-axis) were also examined.

Method

Subjects. The subjects were 16 undergraduates drawn from the same pool used in the previous experiments.

Apparatus. The apparatus was the same as that used in the previous experiments.

Stimuli. The moving targets were the same as in Experiments 1 and 2, except that they vanished after traversing approximately 40% of the distance across the screen. There were 10 possible locations in which the probe could appear. For LR, RL, TB, and BT, these locations were grouped along two axes that were orthogonal to the axis of motion, with five locations along each axis. One group was located 40 pixels (1.7°) further down the axis of motion (the near position) and the second group was 96 pixels (4°) further along the axis of motion (the far position). Within each group, two locations were 12 pixels (30 min) above and below (or right and left) the axis of motion, two locations were 6 pixels (15 min) above and below (or right and left), and one location was centered on the axis of motion. For ULLR, LRUL, URLL, and LLUR, the near position was 30 pixels further along the x-axis (approximately 42 pixels or 1.8° along the oblique axis) and 18, 24, 30, 36, or 42 pixels further along the y-axis; the far position was 72 pixels along the x axis (approximately 102 pixels or 4.2° along the oblique axis) and 60, 66, 72, 78, or 84 pixels along the y axis. This scaling ensured that the magnitude of the distance of the probes in oblique directions approximated the magnitude of the distance of the probes in the horizontal and vertical directions. Target velocity was the same as in Experiment 2. Each subject received 800 trials (8 directions × 2 positions × 5 probe locations × 10 replications) in a different random order.

Procedure. The procedure was the same as in Experiment 2, with the following exceptions: The subjects were instructed to respond *same* if the probe was located along a straight-line extension of the path of the moving target, and to respond *different* if the probe was not located along a straight-line extension of the path of the moving target. A "straight-line extension" was explained to mean that the center of the probe was over a point where the center of the moving target would have passed had it not vanished.

Results and Discussion

There were five possible locations around each position at which the probe could have appeared, and these locations were numbered consecutively 1-5. For LR, RL, ULLR, LRUL, URLL, and LLUR, Locations 1 and 2 were above the path of motion, Location 3 was centered on the path of motion, and Locations 4 and 5 were below the path of motion. For TB and BT, Locations 1 and 2 were left of the path of motion, Location 3 was centered on the path of motion, and Locations 4 and 5 were right of the path of motion. Were subjects responding accurately, there would have been 0% *same* responses on Locations 1, 2, 4, and 5, and 100% *same* responses on Location 3. The alpha level required for significance in all statistical analyses was .01.

The choice probabilities were analyzed using an 8 (directions) × 2 (positions) × 5 (probe locations) repeated measures ANOVA. As shown in Figure 5, probe location clearly affected the probability of a *same* response [$F(4,60) = 41.60$, $MS_e = .14$], but interpretation of this effect must be tempered by the significant interactions of

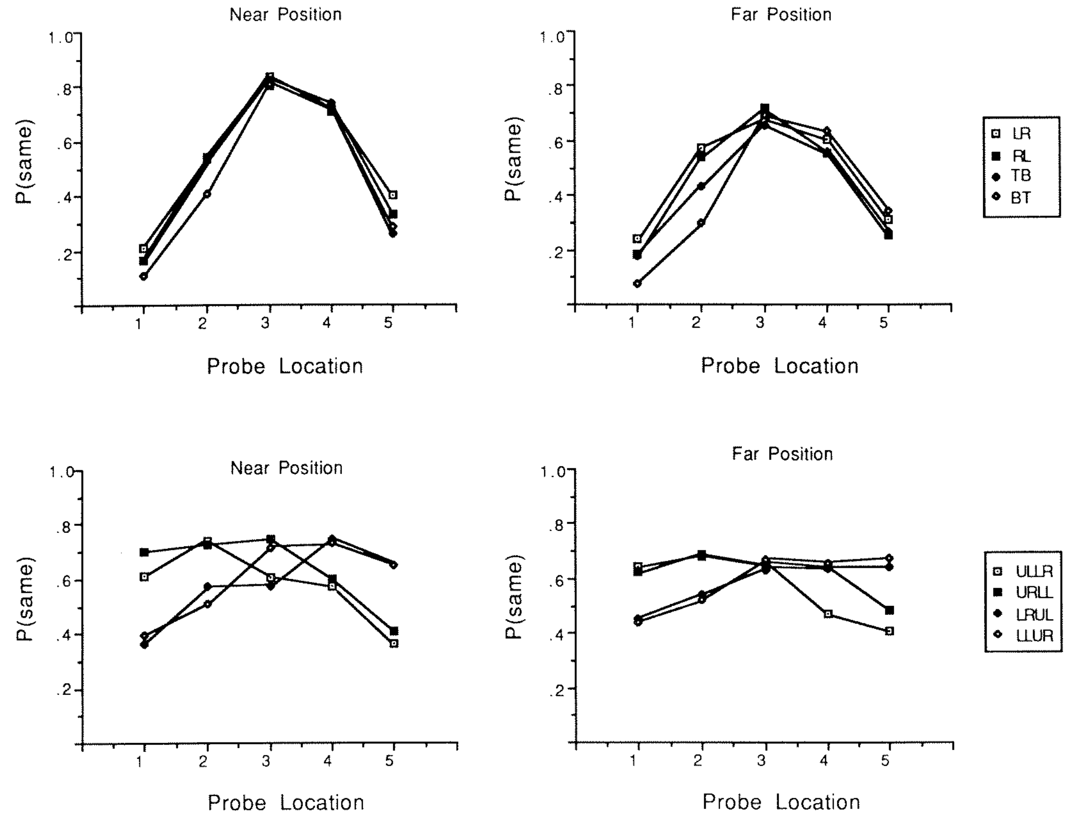

Figure 5. Probability of a *same* response as a function of probe location in Experiment 3. The upper panels display probability for the horizontal and vertical directions, and the lower panels display probability for the oblique directions. The left panels display probability for the near position, and the right panels display probability for the far position.

probe location with direction [$F(28,420) = 10.89$, $MS_e = .05$] and with position [$F(4,60) = 4.66$, $MS_e = .03$]. Post hoc Newman-Keuls tests ($p < .05$) of all pairwise comparisons of probe locations showed that all except Locations 3 and 4 differed significantly from each other. For LR, RL, TB, and BT, the functions are curvilinear, with probes that appeared in Location 3 showing the highest probability of a *same* response; ULLR, LRUL, URLL, and LLUR do not show the strongly curvilinear functions shown by LR, RL, TB, and BT. The probe location × position × direction interaction did not attain significance [$F(28,420) = 1.281$, $MS_e = .02$].

Neither position [$F(1,15) = 2.82$, $MS_e = .12$] nor the position × direction interaction [$F(7,105) = .90$, $MS_e = .03$] significantly affected the probability of a *same* response. Nonetheless, Figure 5 shows that, for the horizontal directions, the probability of a *same* response was higher at the near position than at the far position for a probe slightly below the axis of motion (Location 4). The magnitude of the gravity effect may thus be partially determined by the distance over which the path of motion is extrapolated. Finke and Shyi (1988) did not vary the amount of distance over which their subjects had to extrapolate, but the current data suggest that the effect of the gravity component upon the magnitude of displacement might decrease as the range over which extrapolation occurs increases, at least over the range of distances explored here. A similar pattern is seen in the probability of a *same* response to a probe slightly to the right of the axis of motion for the vertical directions.

Direction of motion influenced the probability of a *same* response [$F(7,105) = 9.71$, $MS_e = .08$]. Planned comparisons revealed that oblique directions resulted in significantly more overall *same* responses than did horizontal and vertical directions [$F(1,15) = 20.59$, $MS_e = .22$]. This result is undoubtedly driven by the relatively lower frequencies of *same* responses to the probes at the ends of each group for the horizontal and vertical directions. As shown in Figure 5, the subjects clearly were able to reject probes at Locations 1 and 5 for horizontal and vertical motion, but these locations had a much higher probability of *same* responses for oblique motion. This may have resulted from the greater Pythagorean distance of Locations 1 and 5 from the axis of motion for the horizontal and vertical directions than for the oblique directions.

For LR and RL motion, particularly at the near position, Location 4 was judged as *same* well over 50% of the time, consistent with the notion of gravity. TB and BT also showed a tendency to have an increased probability of *same* responses on Location 4. This is consistent with the rightward O displacements for TB and BT found in Experiment 1, but the reason for this is unclear. One possibility is that a consistent rightward bias existed among the subjects (perhaps related to the fact that almost all of the subjects were right-handed); this remains an area for future exploration. An interesting pattern emerges from the oblique directions. Ascending oblique directions—LRUL and LLUR—showed a tendency for the probability of a *same* response to increase as probe location was lowered, consistent with gravity. The descending directions, however, showed the reverse trend—the probability of a *same* response decreased as probe location was lowered. Thus, along the axis of gravity, ascending targets were displaced downward, and descending targets were displaced upward. Since this pattern occurred at both the near the far positions, and the near and far positions were on opposite sides of the center of the screen, a bias toward the center of the screen may be ruled out as a possible explanation.

GENERAL DISCUSSION

Consistent with earlier work on the displacement phenomenon, the direction of motion was found to influence the location of the judged vanishing point of a moving target. When subjects positioned a crosshair at the location where they judged the target to have vanished, the overall magnitude of displacement was largest for horizontal motion, intermediate for oblique motion, and smallest for vertical motion. When subjects judged whether a subsequently presented stationary probe along the axis of motion was at the same location at which the target had vanished, the probability of a *same* response for a probe located beyond the vanishing point was higher than the probability of a *same* response for a probe located behind the vanishing point. In addition, vertical motion resulted in higher probabilities of *same* responses than did horizontal or oblique motion. When subjects judged whether a stationary probe located beyond the vanishing point would lie along a straight-line extension of the path of motion (extrapolation task), the probability of a *same* response for a probe located slightly below the path of motion was higher than the probability of a *same* response for a probe located slightly above the path of motion for horizontal and ascending oblique motion, whereas the probability of a *same* response was higher for probes located slightly above the path of motion for descending oblique motion.

The greater probability of *same* responses for vertical motion found in Experiment 2 initially seems to suggest that the vertical motion demonstrated more displacement (since no displacement would lead to *same* responses on only 20% of the trials) than did horizontal and oblique motion, a conclusion opposite to that reached in Experiment 1. This apparent discrepancy, however, can be resolved. Since both horizontal and oblique motion possess larger displacements than does vertical motion (Experiment 1), the target was displaced further ahead of the true vanishing point for horizontal and oblique directions than for vertical directions, thus rendering a greater spatial separation between probes located behind the true vanishing point and the location that the mental representation of the moving target was displaced to. Rejecting probe locations behind the true vanishing point was thus relatively easier for horizontal and oblique directions than for vertical directions (due to the increased forward displacement of the horizontal and oblique directions), accounting for their lower overall probability of *same* responses (see Figure 4). Alternatively, the greater probability of *same* responses for the vertical directions in Experiment 2 may have occurred if the subjects' visual fields exhibited a shorter axis in the vertical direction. Probes at the locations most distant from the center of each group (Locations 1 and 5) would then have been closer to the periphery, and since resolution is less fine in peripheral regions, accurate discriminations would be more difficult and the proportion of correct responses would be expected to decline.

Evidence suggestive of a component of the mental representation equivalent to a gravity influence was found in all of the experiments. In Experiment 1, horizontal motion resulted in a downward displacement in addition to the forward displacement, and top-to-bottom motion resulted in greater forward displacement than did bottom-to-top motion. For oblique motion, ascending directions resulted in less displacement vertically than horizontally. Experiment 2 clearly showed that for the probe locations behind the vanishing point, the highest probability of a *same* response occurred for bottom-to-top motion. Higher probabilities for probe locations behind the true vanishing point would be predicted in the case of bottom-to-top motion, since a rising object would normally be perceived to decelerate. In Experiment 3, the probability of a *same* response was higher for probe locations below the axis of motion for horizontal motion than for probe locations above the axis of motion. Such a pattern is consistent with the idea of a gravitational influence; probe locations slightly below the path of motion (through which a falling target might pass) are more likely to be judged as lying along a straight-line extension than probe locations above the path of motion.

Not all of the evidence initially appeared to support the notion of a gravity effect. For example, descending oblique motion did not exhibit more displacement vertically than horizontally, as a strict gravity-component hypothesis would predict. One possible explanation for this pattern is that displacements for oblique motion are determined in part by two separate effects—a horizontal motion effect and a gravity effect. The horizontal motion effect suggests that the closer the path of motion is to the horizontal axis, the larger the overall displacement will be. The gravity effect suggests that if motion is in a direction parallel with the force of gravity, then the magnitude of displacement will be increased when the direction of motion is consistent with gravity (TB) and decreased when the direction of motion is inconsistent with gravity (BT). When the direction of motion is not parallel to the force of gravity, then the direction of displacement is some combination of the direction of motion and the direction of gravity (e.g., RL and LR are displaced forward and downward). The total displacement for targets undergoing oblique motion would be determined by these two effects—gravity and horizontal motion—working in conjunction. For both ascending and descending oblique motion, displacement along the horizontal axis would be larger than displacement along the vertical axis. For ascending motion, the gravity component would decrease the magnitude of displacement along the vertical axis, thus accentuating the difference between horizontal and vertical displacements. For descending motion, the gravity component would increase the magnitude of displacement along the vertical axis, thus minimizing the difference between horizontal and vertical displacements.

The data do not explicitly address the nature of the mechanism responsible for the displacement phenomenon. One possible mechanism is the presence of eye movements; however, earlier investigators examining analogous "overshooting" of the mental representations of moving lines (Foster & Gravano, 1982) and implied motions of dot patterns (Finke & Freyd, 1985) were able to rule out eye movements as the sole cause of their observed effects. It is possible, nonetheless, that eye movements may play some role; for example, the higher probabilities of *same* responses for probe locations below the path of motion for ascending targets and above the path of motion for descending targets might result from subjects' minimizing their vertical eye movement. Although such an effort-conservation strategy could result in the pattern obtained with the oblique motions, it is not clear how it might account for the patterns found for horizontal and vertical motion. Although eye movements may certainly contribute to the displacement phenomenon documented, there is other evidence of the necessity of a higher order cognitive mechanism in the determination of displacement—namely, that displacement can also be affected by anticipated, as well as actual, direction of motion (Bharucha & Hubbard, 1989).

In conclusion, the previous finding (Hubbard & Bharucha, 1988) that the mental representation of a target traveling in either a horizontal or a vertical direction is displaced in the direction of motion has been extended to include targets traveling in oblique directions. The magnitude of displacement is largest for horizontal motion, intermediate for oblique motion, and smallest for vertical motion. Furthermore, for all directions, the magnitude of the displacement is related to the apparent velocity of the target such that faster apparent velocities result in larger magnitudes of forward displacement. The notion of a component of the mental representation analogous to gravity was supported, as downward displacements along the gravity (y) axis were larger for descending targets and smaller for ascending targets. In addition, representations of targets traveling horizontally were also displaced downward in a manner consistent with gravity. Taken together, the results confirm the importance of direction and velocity as factors in the determination of displacement and extend Shepard's (1984) notion that at least some invariances of the physical world—in this case, gravity—have become incorporated into our mental representations of the world.

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