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Judged displacement in apparent vertical and horizontal motion

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The judged vanishing point of a target traveling along a vertical or horizontal trajectory at uniform velocity was examined. In Experiments 1 and 2, subjects indicated the vanishing point by positioning a cross hair. Judged vanishing point was displaced forward in the direction of motion, and the magnitude of the displacement increased with the apparent velocity of the target. Displacement was greater for horizontal than for vertical motion. In Experiment 3, similar patterns were found using a forced-choice paradigm. Experiments 4 and 5 assessed the role of knowledge of the target's likely behavior. In Experiment 4, the target bounced within the confines of a square frame. Judged vanishing point was displaced in the anticipated direction, even when the anticipated direction was opposite to the current path of motion. Experiment 5 was a control experiment that ruled out the presence of the frame as the sole cause for displacement. The results suggest that displacement from the true vanishing point is due to a high-level cognitive mechanism capable of utilizing knowledge about probable target location.

Knowledge of the principles governing physical motion may take the form of analogue processes (Freyd, 1987; Kelly & Freyd, 1987; Shepard, 1984), and this knowledge may be useful in anticipating the future position of moving objects. Kelly and Freyd (1987) have speculated that the visual system automatically calculates or otherwise extrapolates the future position of a moving object, and Freyd and Finke (1984, 1985) have attributed this extrapolation to a mental analogue of the object's motion that projects the object's representation further in the direction of motion. They have referred to this effect as *representational momentum*.

Freyd and Finke (1984, 1985) found that memory for the final orientation of an object undergoing implied rotation is displaced forward in the direction of implied motion. Their subjects viewed a series of static images that implied rotation of a rectangle, and then indicated the final orientation of the rectangle in a forced-choice task. The subjects were more likely to pick a rectangle rotated slightly beyond the final orientation than one rotated slightly behind or at the true final position. The likelihood of choosing a rectangle rotated beyond the final orientation increased monotonically with implied rotational velocity.

In a related experiment, Finke and Freyd (1985) examined memory for location by presenting dot patterns in which each dot implied motion in a different direction. The forward memory displacement still occurred, suggesting that the effect was not limited to rotational movement. Finke and Freyd also claimed that the effect was due, at least in part, to factors other than pursuit eye movements, because subjects were unable to visually pursue all of the dots simultaneously. Foster and Gravano (1982) obtained a similar result for apparent motion induced between a curved line and a straight line. The transformation of the curved line into the straight line resulted in a perceived reversal of curvature.

In the present paper, we report a series of experiments on the displacement induced by vertical and horizontal apparent motion. There were two primary goals: The first goal was to investigate if systematic displacement could be obtained with apparent linear motion and, if so, if there were influences of the direction of motion. The second, and more important, goal was to explore if displacement could be influenced by knowledge of the target's probable behavior. Forward displacement may be the consequence of a relatively inflexible, forward extrapolation mechanism, suggesting that displacement is the result of modular (Fodor, 1983) or cognitively impenetrable (Pylyshyn, 1981, 1984) processes. Alternatively, displacement may be a consequence of a more flexible, cognitive mechanism that predicts behavior on the basis of knowledge of past behavior or beliefs about future behavior. In the former case, displacement could occur only in the direction of the current path of motion. In the latter case, displacement could occur in a direction different from the current path of motion if the target's past behavior suggests an imminent change of direction.

EXPERIMENT 1

In this experiment, direct estimates of final location were elicited by instructing subjects to pinpoint the vanish-

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ing point of an apparently moving target presented on a video screen. The vanishing point, the center of the target at its final position, was indicated by positioning a cross hair on the screen. Three different velocities were used.

Method

Subjects. Participants in all experiments were Dartmouth College undergraduates who received extra course credit in an introductory psychology course. All subjects were naive as to the hypotheses until their data had been collected, and no subject participated in more than one experiment. Fifteen subjects participated in the present experiment.

Apparatus. The stimuli were presented on an Apple Macintosh computer. The subjects adjusted the viewing distance in order to achieve maximum comfort and confidence in their responses.

Stimuli. The target was a filled circle (black on a white background) 20 pixels (approximately 50′ of arc) in diameter. The display screen was 512×342 pixels (approximately 21°×14°). The target entered from an approximate midpoint of one of the four screen edges and moved across the screen in a straight line. The target vanished at one of five locations that were evenly spaced (60 pixels [150′] for horizontal, 42 pixels [105′] for vertical) along the axes of motion. Vanishing point was counterbalanced across trials. The two horizontal directions were right-to-left (RL) and left-to-right (LR); the two vertical directions were top-to-bottom (TB) and bottom-to-top (BT). Target velocities were obtained by shifts of 1, 3, or 6 pixels between successive images, yielding apparent velocities of 5.8°/sec, 17.4°/sec, and 34.8°/sec, respectively. Each subject received 120 trials (4 directions × 3 velocities × 10 replications) in a different random order.

Procedure. The subjects were run individually. They were first given a practice session consisting of 12 trials selected randomly from the experimental trials. The subjects were instructed: "The ball will disappear from the screen somewhere along its flight path. After the ball has disappeared, the cursor will change to a + sign. Position the cross hair over the place you believe the ball was when it disappeared and click once. Be sure that the center of the cross hair is over the center of the last position of the ball." The subjects initiated each trial by pressing a designated key. The target then appeared at one edge of the screen and traveled toward the opposite side. After the target vanished, the subjects indicated the vanishing point by positioning the cursor over where the target had vanished. The cursor was positioned by a computer mouse; the screen coordinates of the cursor were recorded by pressing a button on the mouse.

A fixation point was not employed because we wanted to avoid any confound of vanishing-point location and eccentricity. If subjects fixated the center of the screen, then displacement could be influenced by differences in acuity as a function of eccentricity; that is, displacements of vanishing points closest to the center would be expected to be less than displacements of vanishing points further from the center, purely on the basis of differing levels of acuity.

Results and Discussion

The difference between judged vanishing point and actual vanishing point is referred to as *displacement*. For each direction of motion, we refer to displacement of the vanishing point along the axis of motion as M displacement, and displacement along the orthogonal axis as O displacement. The mean M displacement is shown in Figure 1. Using a Bonferroni correction for $p < .05$ ($p < .004$), all of the means but one (BT slow, $p = .013$) are significantly greater than zero, demonstrating significant forward M displacement. Faster targets show greater positive M displacement, as shown by a strong velocity effect [$F(2,28) = 49.76$, $MSe = 198.20$, $p < .0001$]. These results extend to apparent vertical and horizontal motion the findings of Freyd and Finke (1984, 1985) that subjects overestimate the final position of a rotating object and that the degree of overestimation is monotonically related to velocity. The velocity functions are steeper for horizontal than for vertical motion, as shown by a significant direction × velocity interaction [$F(6,84) = 10.46$, $MSe = 66.33$, $p < .0001$].

There is a significant effect of direction [$F(3,42) = 34.69$, $MSe = 187.26$, $p < .0001$]. Comparisons between directions (Newman-Keuls, $p < .05$) show that M displacement is greater for horizontal motion than for vertical motion, M displacement is greater for TB than for BT, and M displacement is greater for RL than for LR.

The mean O displacements reveal a significant downward displacement for horizontal motion, but no significant displacement for vertical motion (see Figure 2). Using a Bonferroni correction, O displacements are significantly or marginally significantly different from zero for all horizontal conditions ($p < .004$ for LR slow and medium and for RL slow and fast; $p < .07$ for the

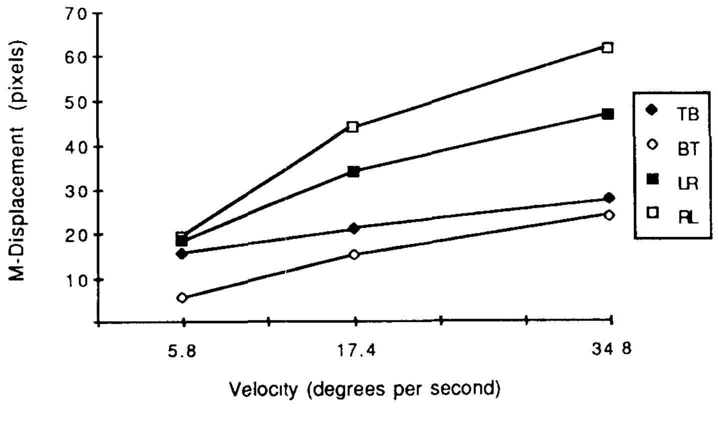

Figure 1. Displacement along the axis of motion (M displacement) as a function of velocity in Experiment 1.

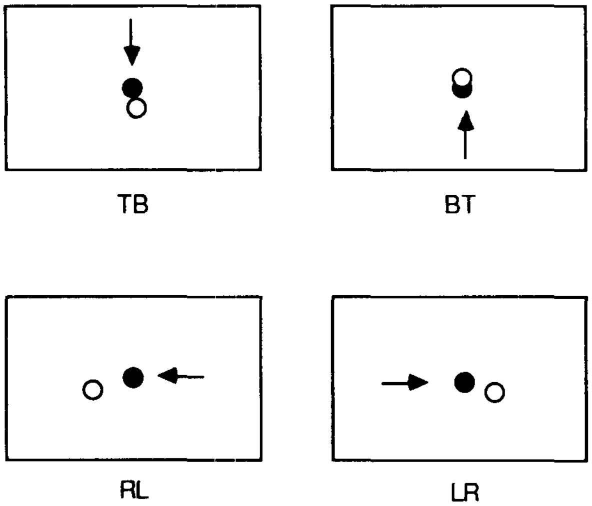

Figure 2. Actual and estimated vanishing point in Experiment 1. The filled circles indicate the target vanishing point; the open circles indicate the average judged vanishing point. The arrow indicates direction of motion, and the rectangle represents the outline of the edges of the screen. Displacement relative to target size is drawn to scale, but target size relative to screen size is not drawn to scale.

remaining two). The downward O displacement for horizontal motion, coupled with greater M displacement for TB than for BT, suggests the notion of an internalization of a downward gravitational influence.

The difference in M displacement between horizontal and vertical motion could be due merely to the difference in screen dimensions; that is, the screen is wider along the horizontal axis than along the vertical axis. Because the spacing of the vanishing points is scaled to the length of the axis of motion, the target is tracked for a longer average duration during horizontal motion than during vertical motion. Another possible influence of screen rectangularity could be the fact that the screen edges, as reference points, are closer along the vertical axis than they are along the horizontal axis. The closer proximity of the edge could result in smaller magnitudes of M displacement.

EXPERIMENT 2

Before concluding that horizontal and vertical motion induce different magnitudes of displacement, we tested the possible role of the rectangular dimensions of the screen by replicating Experiment 1 with a 90° rotation of the screen. Rotating the screen about the line of sight reversed the screen dimensions for horizontal and vertical axes. A reversal in the sign of the observed difference between M displacement for horizontal and vertical motion would rule out a fundamental difference in M displacement for the two axes, and suggest that the rectangularity of the screen was responsible for the difference obtained in Experiment 1. On the other hand, a failure to reverse the difference would suggest a fundamental difference between the two axes. A reduction in magnitude of the difference but a failure to reverse it would suggest both a fundamental difference between the two axes and an effect of screen rectangularity.

To further test the role of screen dimensions, we also introduced vanishing point as an independent variable. (Although vanishing point was counterbalanced in the previous experiment, it was not recorded.) If longer exposure resulted in greater M displacement, then M displacement would increase over successive vanishing points. If proximity to fixed reference points offsets M displacement, the M displacement would first increase (as the target got further from the trailing edge of the screen) and then decrease (as the target got closer to the leading edge of the screen). If Runeson's (1974, 1975) finding for perceived targets—that constant velocity is seen as an initial high velocity followed by a deceleration (stationary physical objects must accelerate before assuming a constant nonzero velocity)—generalizes to apparent motion, then M displacement should decrease over successive vanishing points.

Method

Subjects. The subjects were 15 undergraduates drawn from the same pool as in Experiment 1.

Apparatus. The apparatus from Experiment 1 was mounted at 90° to the horizontal. All other features were the same.

Stimuli. The stimuli were the same as in Experiment 1 except that the spacing between the vanishing points for horizontal and vertical motion was reversed.

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

Results and Discussion

Using a Bonferroni correction, M displacement is significantly greater than zero for all six of the horizontal conditions and five of the vertical conditions (BT slow, $p = .42$). The mean M displacement as a function of vanishing point for each velocity is shown in Figure 3. As in Experiment 1, faster targets show greater M displacement, as indicated by a strong velocity effect [$F(2,28) = 63.94$, $MSe = 54.65$, $p < .0001$]. Unlike Experiment 1, however, there is no significant difference between the slopes of the velocity functions for vertical and horizontal motion [$F(6,84) = .83$, $MSe = 44.92$, $p = .55$].

There is a significant effect of direction [$F(3,42) = 12.74$, $MSe = 197.10$, $p < .001$]. Orthogonal planned comparisons show that M displacement is greater for horizontal motion than for vertical motion [$F(1,42) = 13.87$, $p < .001$]. The difference in M displacement between horizontal motion and vertical motion is not reversed by rotating the screen axes by 90°, although the magnitude of the difference is reduced somewhat. This suggests a fundamentally greater M displacement for horizontal motion as well as an effect of screen rectangularity. For the vertical axis, M displacement is greater for TB than for BT [$F(1,42) = 16.47$, $p < .003$]. For

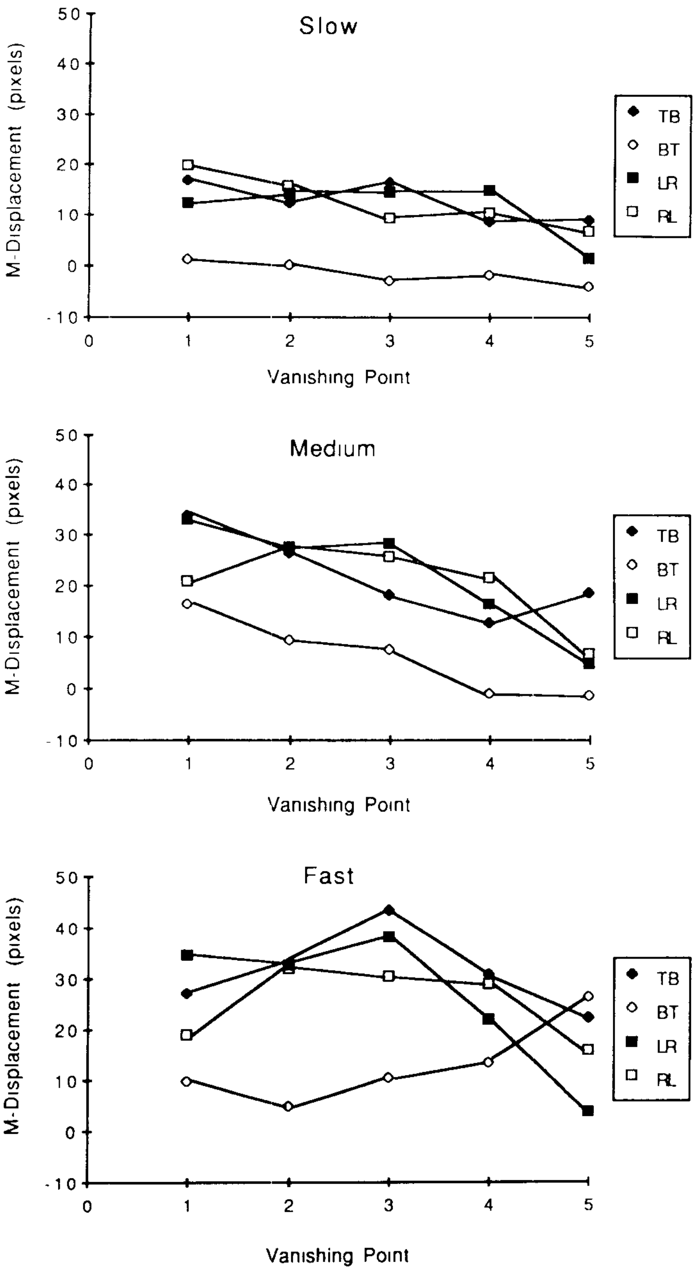

Figure 3. Displacement along the axis of motion (M displacement) as a function of vanishing point in Experiment 2, for slow (top), medium (middle), and fast (bottom) velocities.

the horizontal axis, there is no significant difference in M displacement between LR and RL.

Vanishing point interacts with velocity [$F(8,112) = 2.32$, $MSe = 342.46$, $p < .05$], with direction [$F(12,168) = 5.00$, $MSe = 195.75$, $p < .0001$], and with velocity × direction [$F(24,336) = 2.23$, $MSe = 223.18$, $p < .001$]. For the slow and medium velocities, M displacement decreases slightly as a function of vanishing point, as would be expected for uniform motion, given Runeson's (1974, 1975) results. These conditions thus show no effect of exposure or fixed reference proximity. For the fast velocity, M displacement increases and then decreases as a function of vanishing point for RL, LR, and TB. For fast velocity in BT motion, M displacement increases as a function of vanishing point. M displacement in the fast-velocity condition seems to be influenced by the screen. All directions except BT show an inverted U, suggesting suppressed M displacement as a function of proximity to the screen edge; for BT, M displacement increases as a function of vanishing point, suggesting an effect of exposure. A possible explanation for the increasing BT function may follow from Runeson's results:

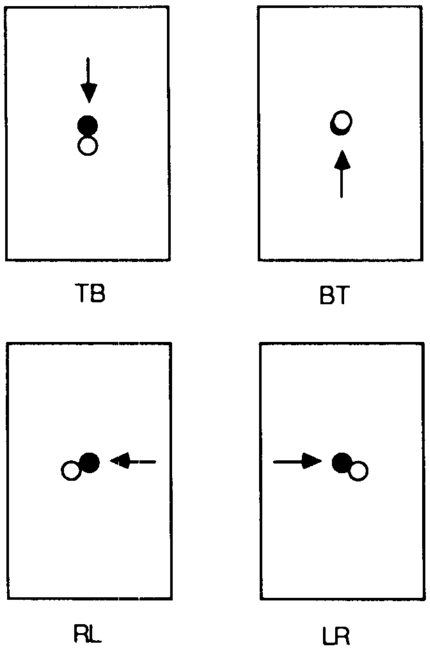

Figure 4. Actual and estimated vanishing point in Experiment 2. The filled circles indicate the target vanishing point; the open circles indicate the average judged vanishing point. The arrow indicates direction of motion, and the rectangle represents the outline of the edges of the screen. Displacement relative to target size is drawn to scale, but target size relative to screen size is not drawn to scale.

Given the typical deceleration of rising objects, a uniform velocity may be perceived as an acceleration.

The mean O displacements reveal a downward trend for horizontal motion but no obvious trend for vertical motion (see Figure 4). Using a Bonferroni correction, the LR slow, medium, and fast velocities and RL medium and fast velocities are marginally significantly different from zero ($p < .03$). The O displacements for the remaining conditions do not approach significance.

As in Experiment 1, horizontal M displacement is larger than vertical M displacement, although the overall magnitudes are slightly reduced. This pattern suggests both an effect of direction and a slight effect of screen rectangularity. As in Experiment 1, TB elicits more M displacement than BT, and horizontal motion elicits a downward O displacement. This pattern is consistent with the idea that gravity is reflected by the mental analogue. The difference between RL and LR M displacement did not replicate. However, inspection of Figure 3 reveals a slightly larger M displacement for RL than for LR at the later vanishing points. It is possible that differences between RL and LR M displacements might develop with longer exposure durations.

EXPERIMENT 3

There are at least two hypotheses which may account for the origin of the displacements measured in Experiments 1 and 2. The first hypothesis is that displacements are peculiar to the cursor-positioning paradigm, and the second hypothesis is that displacements result from memory shifts of the type proposed by Freyd and others. The design of Experiment 3 was similar to that of Experiment 1, except that two stationary targets were presented after the moving target had vanished. Subjects judged which of the stationary targets was located at the vanishing point. Since one of the alternatives was the true vanishing point, this task eliminates factors peculiar to the recall of Experiments 1 and 2.

Method

Subjects. The subjects were 16 Dartmouth College students drawn from the same pool as in Experiments 1 and 2.

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

Stimuli. The target was the same as in Experiment 1. After the target vanished, two circles of the same size and appearance as the target appeared simultaneously on the screen. One alternative (the stationary target) was presented at the vanishing point, and the other alternative (the distractor) was presented 20 pixels (50′) further along in the direction of motion. Each subject received 120 trials (4 directions × 3 velocities × 10 replications) in a different random order.

Procedure. The procedure was the same as in Experiment 1 with the following exceptions: After the target vanished, the screen remained blank for 2 sec. This delay was based on pilot measurements of the response latencies for the paradigm used in Experiments 1 and 2. The stationary target and the distractor then appeared and remained on the screen until the subject responded. The subject pressed one of two designated keys to indicate which of the alternatives was at the vanishing point.

Results and Discussion

The probability of choosing the distractor is shown in Figure 5. With a Bonferroni correction for $p < .05$, choice probability is greater than chance (.5) for the medium and fast velocities of the horizontal conditions (RL slow, $p = .12$; LR slow, $p = .29$). For the vertical conditions, the probability of choosing the distractor is significantly less than chance for BT slow; no other vertical condition differs from chance. A lack of preference for the distractor for the vertical conditions and slow velocities of the horizontal conditions, however, does not indicate an absence of a memory displacement, since there is no significant preference for the correct alternative, either.

The overall velocity effect is substantiated by the forced-choice paradigm. The probability of choosing the distractor increases with velocity [$F(2,30) = 11.64$, $MSe = 5.13$, $p < .001$], although performance reaches a plateau after the medium velocity. For LR, the velocity function is flat throughout, as indicated by a significant velocity × direction interaction [$F(6,90) = 2.48$, $MSe = 2.20$, $p < .03$]. Freyd and Johnson (1987) found a higher rate of decay of displacement for fast velocities, and this faster decay may be responsible for the apparent plateauing in the current experiment. Although initial M displacement may have been greater for fast velocities, the higher rate of decay would have reduced fast-velocity M displacement more than medium-velocity M displacement by the

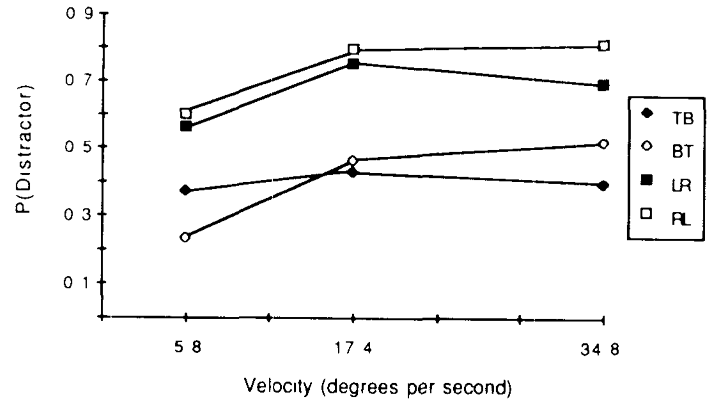

Figure 5. Probability of choosing the distractor as a function of velocity in Experiment 3.

time the stationary target and distractor were presented, rendering the two levels of M displacement nearly equal. Alternatively, the absence of a plateauing in the velocity effect in the free-response paradigm used in Experiments 1 and 2 may implicate a bias over and above memory displacement. This conclusion seems plausible because response latency for the response paradigm of Experiments 1 and 2 is comparable to the latency between the offset of the moving target and the onset of the stationary target and distractor in Experiment 3.

The effect of direction is highly significant [$F(3,45) = 21.70$, $MSe = 6.80$, $p < .0001$]. Orthogonal planned comparisons show that the probability of choosing the distractor is significantly greater for horizontal motion than for vertical motion [$F(1,45) = 63.54$, $p < .0001$]. The differences between horizontal and vertical motion are borne out in the forced-choice paradigm; horizontal motion induces significantly more M displacement than does vertical motion. The difference between RL and LR found in Experiment 1 and TB and BT in Experiments 1 and 2 failed to replicate, suggesting that these may be due to task-specific factors.

In sum, task-specific factors alone cannot account for the M-displacement effects. The two primary findings of Experiments 1 and 2—namely, a velocity effect (faster velocities lead to larger magnitudes of M displacement) and a direction effect (horizontal motion exhibits larger M displacement than vertical motion)—are substantiated by the two-alternative forced-choice paradigm.

EXPERIMENT 4

In this experiment we sought to determine whether M displacement was due to either (1) a low-level mechanism limited to forward extrapolation of the target's current motion, or (2) a high-level cognitive mechanism that adapts to changes in direction or behavior of the target. The critical difference between these alternatives is this: If displacement is due solely to a low-level forward extrapolation mechanism, then knowledge of probable future position should have no effect on the direction of displacement; displacement should always be forward extrapolation along the current path of motion. If, however, the displacement is due to knowledge of probable future position, as predicted by the high-level cognitive hypothesis, then knowledge of probable future position should determine the direction of displacement.

This distinction may have implications for whether or not the processes responsible for displacement are modular in the sense of being informationally encapsulated (Fodor, 1983) or cognitively impenetrable (Pylyshyn, 1981, 1984). Freyd (1987; Kelly & Freyd, 1987) has argued that representational momentum is modular, that is, immune to task expectations. However, the location of expected future position has never been explicitly manipulated. It is possible that if subjects believe that the target will change direction, displacement may occur in the anticipated, rather than the current, direction of motion.

In Experiments 1, 2, and 3 probable future position was always a forward continuation of the target's path. In Experiment 4, we manipulated the direction of expected future position by having the target "bounce off" a wall. The target vanished either just prior to collision with the walls of a frame (precollision), at the moment of impact (collision), or just after bouncing back from the frame (postcollision). In the precollision and collision conditions, the expected future position was in the direction opposite to that in which the target was currently moving. In the postcollision condition, the expected future position was in the same direction in which the target was currently moving.

We defined the sign of M displacement as follows: M displacement is positive if the judged vanishing point is displaced in the direction of current motion. M displacement is negative if the judged vanishing point is displaced in the direction opposite to current motion. If the M-displacement effect is due to knowledge of future position, one would predict negative M displacement at precollision and collision and positive M displacent at postcollision. If, however, the M displacement is always a forward extrapolation, then one should predict positive M displacement regardless of whether the target vanishes prior to or after a bounce.

Method

Subjects. The subjects were 18 Dartmouth College undergraduates from the same pool as in the previous experiments.

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

Stimuli. A target of the same specifications used in the previous experiments was employed. One velocity, which corresponded to a shift of approximately 2.5 pixels per presentation (14.5°/sec), was used. In addition to the target, a square frame (300 × 300 pixels; 12.5° × 12.5°) was drawn on the screen. The target moved horizontally or vertically at a constant velocity within the confines of the frame and appeared to bounce off the inside of the frame. The target bounced from one to five times before it and the frame vanished simultaneously. The target vanished at one of three locations relative to the nearest wall of the frame: precollision, collision, and postcollision. The precollision condition occurred when the target was approaching the frame, the collision condition occurred at the moment of impact against the frame, and the postcollision occurred when the target had bounced off the frame. The pre- and postcollision vanishing points were both located 40 pixels (100′) away from the frame. Each subject received 300 trials (4 directions × 3 vanishing points × 5 bounces × 5 replications) in a different random order.

Procedure. The procedure was the same as in Experiment 1 with the following exceptions: When subjects initiated a trial, the target and the frame appeared simultaneously. The target appeared within the confines of the frame and bounced from one to five times before it and the frame vanished simultaneously.

Results and Discussion

The mean M displacement is shown in Figure 6. Using a Bonferroni correction, all of the M displacements at the collision vanishing point are significantly less than zero ($p < .004$). For postcollision, M displacements for the two horizontal directions are significantly greater than zero, and M displacements for the two vertical directions are marginally significantly greater than zero ($p < .02$). For precollision, the M displacement for LR is significantly less than zero, but M displacements for the other directions do not differ significantly from zero.

The effect of vanishing point on M displacement is highly significant [$F(2,34) = 41.61$, $MSe = 1{,}085.45$, $p < .0001$]. Post hoc comparisons (Newman-Keuls, $p < .05$) show all pairwise comparisons to be significant. Thus, M displacement is negative for the precollision and collision vanishing points, whereas M displacement is positive for the postcollision vanishing point. These results support the existence of a cognitive mechanism capable of adapting to changes in direction, and lead us to reject the hypothesis that M displacement is a consequence solely of a low-level forward extrapolation mechanism.

It is interesting to note that the magnitude of the backward displacement is larger in the collision than in the precollision condition. This strengthens the claim that subjects are anticipating future position at a cognitive level, because a target that is closer to the frame is more likely to bounce (i.e., change direction) sooner and then travel further in the postbounce direction than a target that is farther from the frame. However, the type of anticipation is not clear. The negative M displacements obtained at precollision and collision vanishing points may be due to the mental analogue of the target that has already bounced. Alternatively, the negative M displacement may be due to the mental analogue "putting on the brakes" to avoid impact with the frame. In the former case, the mental representation is distorted forward and then bounces back, but in the latter case, the mental representation is simply distorted backward. At any rate, M displacement at precollision and collision clearly shows the effects of an anticipation of some sort.

There is a significant effect of direction [$F(3,51) = 4.03$, $MSe = 55.43$, $p < .02$], and a vanishing point × direction interaction [$F(6,102) = 8.49$, $MSe = 158.38$, $p < .0001$]. Horizontal directions yield greater negative M displacement than vertical directions at collision and

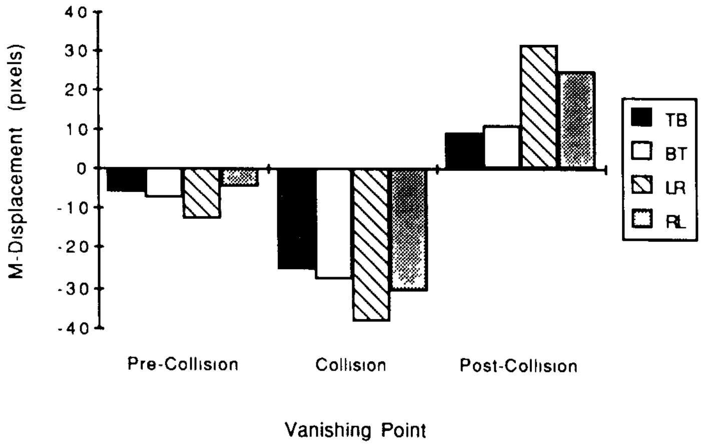

Figure 6. Displacement along the axis of motion (M displacement) as a function of vanishing point in Experiment 4.

greater positive M displacement at postcollision. Thus, horizontal motion once again exhibits greater levels of M displacement.

As shown in Figure 7, there is a consistent, albeit nonsignificant, downward drift in the O displacements for LR and RL, consistent with the apparent gravity effect observed earlier. Using a Bonferroni correction, none of the O displacements differ significantly from zero ($p > .004$).

The results show that M displacement cannot be due solely to a low-level modular forward-extrapolation mechanism. Significant positive M displacement is obtained when anticipated future position is in the current direction of motion, and significant negative M displacement is obtained when anticipated future position is in the direction opposite to the current direction of motion. The direction of M displacement therefore appears to be dependent upon knowledge of probable future position. The displacement effect appears to be at least partially cognitively penetrable.

EXPERIMENT 5

This experiment tested the possibility that the M displacement pattern found in Experiment 4 was due to the mere presence of the frame and did not require any knowledge of an impending bounce. In this experiment, we presented the same target and frame, but eliminated the bouncing motion. Instead of seeing the target bouncing within the frame, subjects saw the target enter from one side of the screen and crash through at least one, and sometimes two, walls of the frame. If the presence of the frame was responsible for the pattern of M displacements found in Experiment 4, then M displacements for precollision and collision vanishing points should be negative. If, however, knowledge of the target's bouncing motion

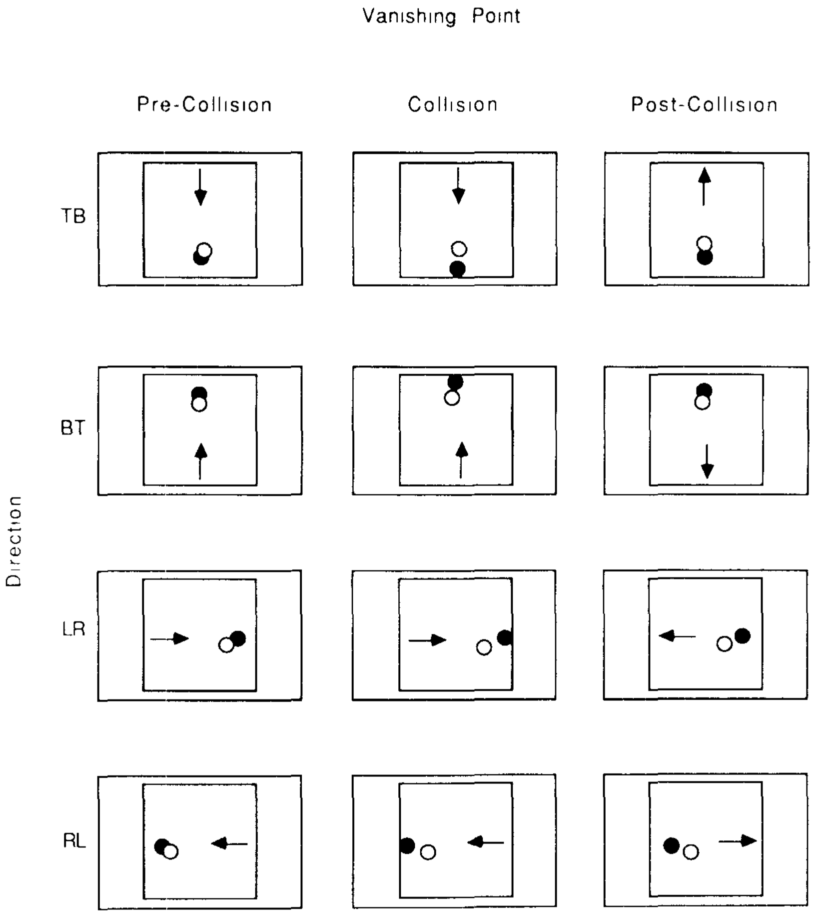

Figure 7. Actual and estimated vanishing point in Experiment 4. The filled circles indicate the target vanishing point; the open circles indicate the average judged vanishing point. The arrow indicates direction of motion, and the rectangle represents the outline of the edges of the screen. Displacement relative to target size is drawn to scale, but target size relative to screen size is not drawn to scale.

was responsible for the direction of M displacement, then M displacements for precollision and collision vanishing points should be positive.

Method

Subjects. The subjects were 15 Dartmouth College undergraduates from the same pool used in the previous experiments.

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

Stimuli. The target and frame were the same as in Experiment 4 Because of the rectangularity of the screen and of the relatively large size of the frame, only the horizontal directions were utilized. The target appeared at the approximate midpoint of either the left or the right edge of the screen and moved across the screen at a constant velocity There were four vanishing points: initial, precollision, collision, and postcollision. Initial occurred after the target had crashed through the first wall of the frame and had traveled an additional 40 pixels (100′). Precollision occurred after the target had crashed through the first wall and was approaching the second wall. Collision occurred at the moment of impact against the second wall. Postcollision occurred after the target had crashed through the first and second walls of the frame and had traveled beyond the second wall. Precollision and postcollision vanishing points were located 40 pixels (100′) on either side of the second wall of the frame. Each subject received 120 trials (2 directions × 4 vanishing points × 15 replications) in a different random order.

Procedure. The prcedure was the same as in Experiment 4 with the following exceptions: The target appeared at either the left or the right edge of the screen (simultaneously with the appearance of the frame). The target then moved across the screen and crashed through the first wall of the frame. The target continued in motion until it vanished at one of the four vanishing points.

Results and Discussion

The mean M displacement is shown in Figure 8. None of the M displacements are significantly negative. Using a Bonferroni correction for $p < .05$ ($p < .0064$), four of the eight M displacements are significantly positive. For RL, initial, precollision, and postcollision show significant forward displacement (collision, $p < .10$). For LR, only initial shows significant forward displacement (precollision, $p < .12$; collision, $p > .96$; postcollision, $p < .22$).

The effect of vanishing point on M displacement is highly significant [$F(3,42) = 15.87$, $MSe = 162.91$, $p < .0001$]. Post hoc comparisons (Newman-Keuls, $p < .05$) show that this is due to the initial condition, which possesses significantly greater positive M displacement than all other conditions. No other pairwise comparisons are significant. It is important to note that there is no difference between the precollision, collision, and postcollision conditions. In Experiment 4, the corresponding vanishing points yielded radically different displacements. In that experiment, the target bounced off the wall of the frame, so subjects anticipated the change of direction. Had this effect been due solely to the presence of the wall per se, then a similar pattern should have been found in Experiment 5. Therefore, M displacement must be due to factors other than a low-level forward extrapolation or the mere inhibitory presence of the wall.

As in Experiment 1, RL leads to significantly larger forward M displacements than LR [$F(1,14) = 4.91$, $MSe = 225.69$, $p < .05$]. However, the failure of this effect to replicate in the forced-choice experiment suggests that this assymetry may result from task-specific factors. The velocity × direction interaction failed to reach significance [$F(3,42) = .60$, $MSe = 46.37$, $p < .62$].

Consistent with the earlier experiments, O displacement shows a downward trend (see Figure 9). However, using a Bonferroni correction, none of the O displacements are significantly different from zero ($p > .004$).

In sum, the results of this experiment suppport the hypothesis that knowledge of future position, rather than the presence of the frame per se, determines the direction of M displacement. It is important to note that even though in the present experiment, the precollision and the collision M displacements do not differ significantly from zero, they clearly do not demonstrate the pattern that was found in Experiment 4. Although passage through the frame somewhat attentuates forward M displacement, it does not reverse its direction. Therefore, the mere presence of the frame cannot account for the pattern of M displacements.

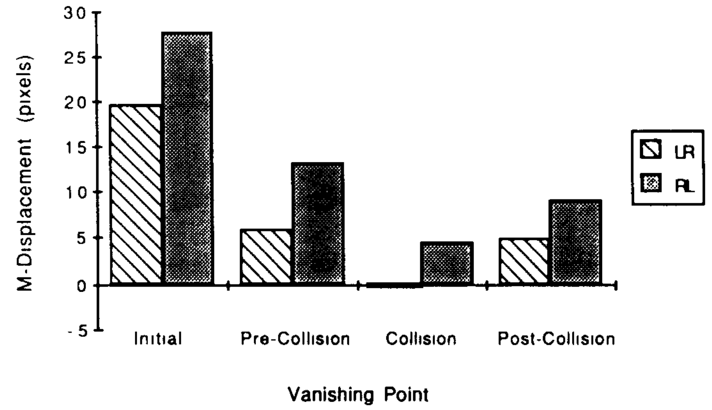

Figure 8. Displacement along the axis of motion (M displacement) as a function of vanishing point in Experiment 5.

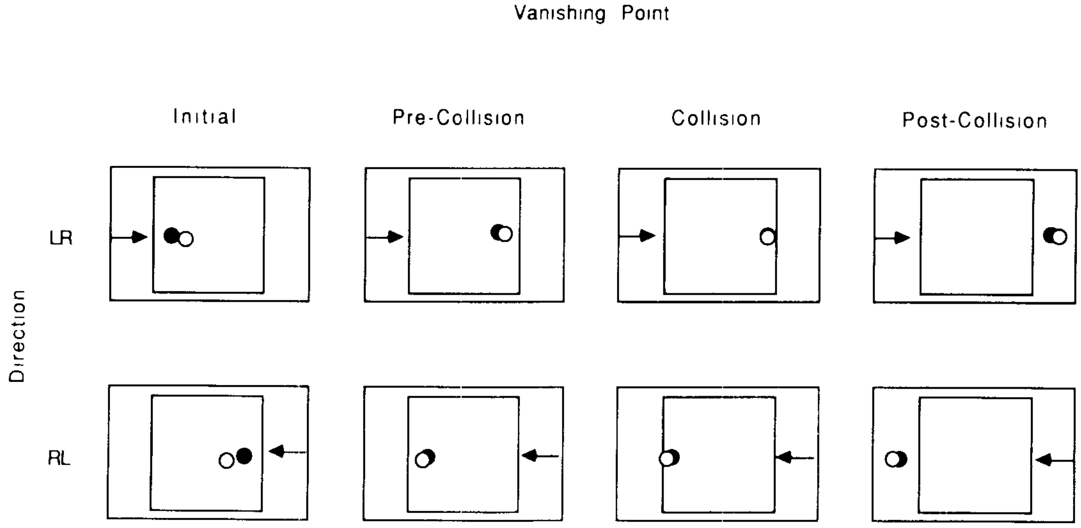

Figure 9. Actual and estimated vanishing point in Experiment 5. The filled circles indicate the target vanishing point; the open circles indicate the average judged vanishing point. The arrow indicates direction of motion, and the rectangle represents the outline of the edges of the screen. Displacement relative to target size is drawn to scale, but target size relative to screen size is not drawn to scale.

GENERAL DISCUSSION

Memory for the location of an object in apparent vertical or horizontal motion is displaced along the direction of motion, consistent with earlier findings for implied rotational motion (Freyd & Finke, 1984, 1985) and apparent motion of lines (Foster & Gravano, 1982). The magnitude of this displacement is related to the velocity of the target, such that faster velocities lead to larger forward displacements. The magnitude of the forward M displacement is also affected by the direction in which the object moves, with horizontal directions yielding larger M displacements than vertical directions. Additionally, there is a tendency for downward displacement for horizontal motion.

M displacement cannot be accounted for solely by a low-level modular forward-extrapolation mechanism, since backward displacement occurs when a subject believes a bounce is imminent. Furthermore, it is knowledge of an impending change of direction, rather than the presence of a boundary (the frame) per se, that determines the reversal in M displacement; when subjects believed the target would crash through the frame, we did not obtain significant levels of negative displacement. It is not clear if M displacement occurs because the mental representation of the target slows down in anticipation of collision or because the representation depicts the target as having already bounced. The data here cannot distinguish between these two alternatives, but we have examined this issue in greater detail elsewhere.[1]

In the forced-choice experiment, subjects were not allowed to respond until 2 sec after the target had vanished. This interval is much longer than the time course of memory displacements for implied rotational movement. Freyd and Johnson (1987) have shown that, for rotational motion, memory displacement reaches a maximum within 300 msec and then rapidly declines. In Experiment 3, the interval between the disappearance of the target and the subjects' responses was far longer than the effective temporal range suggested by Freyd and Johnson, suggesting that memory displacements for horizontal and vertical apparent motion can persist for longer periods of time.

Sensory phenomena that could influence performance on these tasks—motion aftereffects (Beverley & Regan, 1979), afterimages on the computer screen, and persistence of vision—would all serve to counteract the forward displacement. M displacement thus seems to involve knowledge of the future position of the moving target, implicating a high-level cognitive mechanism that predicts the future position of a moving target on the basis of knowledge of its previous pattern of behavior. A more convincing demonstration of nonmodularity of M displacement would occur if displacement pattern could be altered solely by changes communicated verbally (without changing the physical display); we are currently further investigating this possibility.

Although Foster and Gravano (1982) and Freyd (1987) rejected eye-movement explanations for the displacement effects they obtained, the role of eye movements in M displacement is uncertain. It is possible that, in the current experiments, judged vanishing point may have been determined partly by final eye fixation following tracking, especially since eye position is known to play an important role in the perception of visual direction (Matin, 1986; Skavenski & Hansen, 1978). If this is true, the final eye fixation cannot be based on simple forward inertia of the eyes, because M displacement is in the direction opposite to the direction of motion when a bounce is anticipated. Thus, if eye-fixation information influences subjects' judgments, eye movements themselves must be driven by a cognitive mechanism that predicts future position. Even if final eye fixation is, indeed, found to correspond to judged vanishing point, it is unclear as to whether the judgment is influenced by eye fixation or directly by the cognitive system guiding eye fixation. The bounce manipulation implicates a high-level nonmodular cognitive controlling mechanism in either case.

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NOTE

1 Bharucha and Hubbard (1988) presented a target that approached the wall at an incident angle of 45°. The target was displaced forward along the axis parallel to the wall, but was displaced backward along the axis perpendicular to the wall.

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