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Target Size and Displacement Along the Axis of Implied Gravitational Attraction: Effects of Implied Weight and Evidence of Representational Gravity

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Effects of target size on displacements between the actual and remembered vanishing points of moving and stationary targets were examined. For horizontally or vertically moving targets, target size influenced displacement only along the axis aligned with the direction of implied gravitational attraction; larger targets exhibited greater downward displacement when targets moved horizontally, greater forward displacement when targets descended, and smaller forward displacement when targets ascended. For stationary targets, target size did not influence displacement along the axis aligned with the direction of implied gravitational attraction. The data are consistent with the hypothesis that mental representation incorporates an analogue of weight. It is proposed that weight, rather than mass, influences displacement because the representational system incorporates subjective or experiential aspects of physical principles rather than physical principles per se.

An observer who perceives a target that is moving in a consistent direction will usually remember that target as having traveled slightly further than it actually did; in other words, memory for the final orientation or location of a target will be slightly displaced in the direction of anticipated target motion (for a review, see Hubbard, 1995b). Early explanations of this displacement drew on parallels between the physical momentum of a moving target and an analogous momentum within the representational system, and so the displacement was referred to as *representational momentum* (e.g., Freyd & Finke, 1984). Indeed, Finke, Freyd, and Shyi (1986; Finke & Freyd, 1989) suggested that representational momentum resulted from an internalization of the laws of physical momentum by the representational system. More recent investigations have suggested that displacement reflects more than just an internalization of the laws of momentum (e.g., Hubbard, 1994; Verfaillie & d'Ydewalle, 1991), and investigators have proposed explanatory frameworks that rely on dynamic properties of the spatiotemporal coherence between represented and representing worlds (Freyd, 1987, 1992, 1993) and on a combination of stimulus characteristics, implied dynamics and environmental invariants, memory averaging, and observers' expectations (Hubbard, 1995b).

To the extent that an internalization of the laws of physical momentum contributes to representational momentum, then factors that influence physical momentum should also be found to influence representational momentum. Physical momentum is defined as the product of an object's velocity and mass, and so we could predict that both the velocity and the mass of the target should influence representational momentum. Previous researchers have reported robust effects of target velocity on representational momentum (e.g., Freyd & Finke, 1985; Hubbard, 1990, 1996; Hubbard & Bharucha, 1988), but effects of target mass on representational momentum have been more difficult to document. Cooper and Munger (1993) presented experimental participants with rectangular stimuli undergoing either implied rotation or implied horizontal translation, but differences in representational momentum as a function of stimulus size were not observed. Pantzer and Freyd (1989) presented experimental participants with pictures of similarly sized objects varying in implied mass (e.g., a block of styrofoam vs. a block of brick), but differences in representational momentum as a function of these conceptual manipulations of implied mass were not observed.

Cooper and Munger's (1993) and Pantzer and Freyd's (1989) data suggest that target mass does not influence representational momentum. However, representational momentum is only one component of the ultimate displacement of a target, and so it is possible that target mass might influence the more general displacement of a target even though it doesn't influence representational momentum per se. Hubbard (1995a, Experiments 4 and 5) examined displacements along both the axis of motion and the axis orthogonal to motion for horizontally moving targets of different sizes; no effect of target size was found on displacement along the axis of motion (i.e., the horizontal axis), but the magnitude of downward displacement along the orthogonal axis (i.e., the vertical axis) was greater for larger targets than for smaller targets. The orthogonal axis in Hubbard's experi-

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ments was aligned with the direction of implied gravitational attraction, and the differences in the effects of target size and implied mass in the experiments of Cooper and Munger, Pantzer and Freyd, and Hubbard might be accounted for if displacement is sensitive to the effects of target size and implied mass only along the axis aligned with the direction of gravitational attraction.

Why might displacement be sensitive to effects of target size and implied mass only along the axis aligned with the direction of gravitational attraction? One possible explanation is that observers respond not to the implied *mass* (which should influence momentum regardless of direction of travel) but to the implied *weight* (which is felt in the direction of gravitational attraction) of the target. Weight is defined as the product of mass and (the acceleration due to) gravity; indeed, if observers were responding to weight rather than to mass, then effects of target size and implied mass should have been observed only along the axis of implied gravitational attraction. Although the momentum metaphor suggests that observers have accurately incorporated an analogue of mass into their representations, it may have been easier or simpler for the representational system to have instead incorporated an analogue of the experience of mass, that is, an analogue of weight. The hypothesis that effects of mass have been internalized as effects of weight can account for the failure of previous attempts to document effects of target size and implied mass on representational momentum, and it also predicts that effects of target size should be felt only along the axis aligned with gravitational attraction.

In the following experiments, observers were presented with computer-animated targets of varying sizes, and the effects of target size on displacement were measured along the horizontal and vertical axes. Given the constraints of the picture plane display, targets could vary in two-dimensional surface area, but targets could not vary in three-dimensional volume or density. Thus, mass and weight were only indirectly manipulated and controlled. However, a long tradition of research on the size–weight illusion (e.g., Koseleff, 1957; Masin & Crestoni, 1988; Woodworth, 1921) suggests that visually larger physical objects are perceived to be heavier than visually smaller objects, and this bolsters confidence that targets exhibiting larger two-dimensional surface areas are perceived as more massive and heavier than targets exhibiting smaller two-dimensional surface areas. If observers' representations include analogues of mass or weight, and if manipulations of target size are effective in inducing different perceived masses or weights, then we would predict that larger targets should exhibit greater displacement along the axis aligned with the direction of gravitational attraction. Failure to observe effects of target size along the axis aligned with the direction of gravitational attraction would suggest that analogues of mass or weight are not incorporated into the representation or, alternatively, that manipulations of target surface area designed to imply changes in target mass and weight are not effective.

Experiment 1

Hubbard (1995a) reported that larger horizontally moving targets exhibited greater downward displacement than did smaller horizontally moving targets; however, in those experiments much larger stationary objects (referred to as "surfaces" in the original report) were often concurrently presented above or below the target's path of motion. To demonstrate that the larger downward displacements exhibited by larger targets were due solely to the size of the targets, it is necessary to examine the displacements of targets that are presented in isolation.[1] Accordingly, in Experiment 1, observers saw horizontally moving targets that varied in size and velocity across trials. If an analogue of mass was incorporated into the representation, then larger targets should exhibit greater forward displacement than smaller targets along the axis of motion. If an analogue of weight was incorporated into the representation, then larger targets should exhibit greater downward displacement than smaller targets. If analogues of neither mass nor weight were incorporated into the representation, or if the effects of target size observed in Hubbard's experiments were due to contributions from the larger stationary objects presented concurrently with the targets, then target size should not influence forward or downward displacement.

Method

Participants. The observers were 10 undergraduates from Texas Christian University who participated in return for partial course credit in an introductory psychology course. All observers were naive to the hypothesis until after their data had been collected.

Apparatus. The stimuli were displayed on and data were collected by an Apple Macintosh IIsi microcomputer equipped with an Apple RGB color monitor.

Stimuli. The target stimulus was a filled black square presented on a white background. The target squares were 20, 30, 40, 50, or 60 pixels (approximately 0.83°, 1.25°, 1.67°, 2.08°, or 2.50°) in diameter on each trial. On each trial, the target either (a) emerged from the approximate midpoint of the left edge of the screen and moved rightward or (b) emerged from the approximate midpoint of the right edge of the screen and moved leftward. The target crossed approximately half of the horizontal extent of the screen before it vanished without warning. Target velocity was constant within a trial and varied between trials. Target velocity was controlled by shifting the target 1, 2, or 3 pixels between successive presentations, thus resulting in an apparent velocity of approximately 2.5°/s, 5°/s, or 7.5°/s. Each participant received 240 trials (2 directions × 3 velocities × 5 sizes × 8 replications) in a different random order.

Procedure. Observers were first given 12 practice trials at the beginning of the session, and the practice trials were drawn randomly from the experimental trials. The observers initiated each

[1] Even though targets were presented in isolation in some of the conditions in Hubbard's (1995a) article, it is still possible that displacement on those trials may have been influenced by memory for other trials in which the larger stationary objects were presented. Thus, it is desirable to measure effects of target size on displacement in a group of observers that has not experienced any previous exposure to the larger stationary objects.

trial by pressing a designated key, and after a 1-s pause the target emerged from either the left or the right edge of the screen and traveled across the screen. Observers were instructed to watch the target. The target vanished without warning. The cursor, in the form of a plus sign, appeared near the center of the screen, and observers were instructed to position the center of the cursor over where the center of the target had been when the target vanished. The cursor was positioned by the movement of a computer mouse, and after positioning the mouse, the observers clicked a button on the mouse to record the screen coordinates of the cursor. Observers then initiated the next trial.

Results

The differences between the true vanishing point and the judged vanishing point in pixels along the x- and y-axes were calculated for each target. Consistent with previous reports, the differences along the axis of motion (the x-axis) are referred to as *M displacement*, and the differences along the axis orthogonal to motion (the y-axis) are referred to as *O displacement*. Positively signed M displacements indicate judged vanishing points beyond the true vanishing point (i.e., left of a leftward target, right of a rightward target), and negatively signed M displacements indicate judged vanishing points behind the true vanishing point (i.e., right of a leftward target, left of a rightward target). Positively signed O displacements indicate judged vanishing points above the true vanishing point, and negatively signed O displacements indicate judged vanishing points below the true vanishing point.

M displacement. The M displacement scores were analyzed with a 2 (direction) × 3 (velocity) × 5 (size) repeated measures analysis of variance (ANOVA) and are displayed in Figure 1. Velocity influenced M displacement, $F(2, 16) = 5.79$, $MSE = 78.05$, $p < .01$; a post hoc Newman–Keuls test ($p < .05$) revealed that the fast ($M = 15.37$) velocity produced greater positive M displacement than the slow ($M = 11.12$) velocity, and neither the fast nor the slow velocities were significantly different from the medium ($M = 13.37$) velocity. Consistent with previous reports, increases in target velocity led to increases in the magnitude of positive M displacement. Size did not influence M displacement, $F(4, 32) = 0.46$, $MSE = 63.16$, $p = .76$, nor were any other variables significant.

O displacement. The O displacement scores were analyzed with a 2 (direction) × 3 (velocity) × 5 (size) repeated measures ANOVA and are displayed in Figure 1. Size significantly influenced O displacement, $F(4, 32) = 2.70$, $MSE = 11.42$, $p < .05$; a post hoc Newman–Keuls test ($p < .05$) revealed that the 60-pixel ($M = -4.71$) target produced greater negative O displacement than the 20-pixel ($M = -2.82$) target, and neither the 60-pixel target nor the 20-pixel target was significantly different from the 50-pixel ($M = -4.27$), 40-pixel ($M = -3.84$), or 30-pixel ($M = -3.65$) targets. Increases in target size led to increases in the magnitude of negative (i.e., downward) O displacement. Also, rightward ($M = -4.99$) targets produced greater negative O displacement than leftward ($M = -2.73$) targets, $F(1, 8) = 18.03$, $MSE = 21.34$, $p < .01$. No other variables were significant.

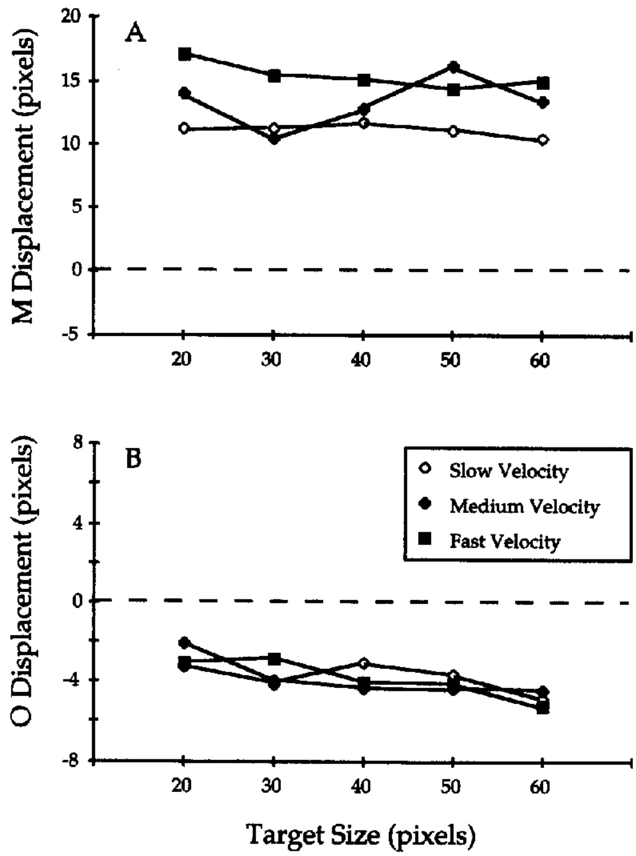

Figure 1. Displacement as a function of target size in Experiment 1. A: M displacement data; B: O displacement data.

Discussion

Target size did not influence M displacement, and this finding is consistent with Cooper and Munger's (1993) and with Pantzer and Freyd's (1989) failures to find effects of implied target mass on representational momentum. Target size influenced O displacement such that larger targets exhibited greater magnitudes of negative O displacement, and this finding is consistent with the hypothesis that effects of target size and implied target mass are seen along the axis aligned with the direction of implied gravitational attraction. The targets in Experiment 1 were presented on a relatively featureless background, and so the effects of target size observed in Hubbard's (1995a) experiments cannot be attributed to the presence of the larger stationary objects in those experiments. The presence of effects of target size along the axis aligned with gravity and the absence of effects of target size along the horizontal axis support the hypothesis that effects of mass may have been internalized as effects of weight.

Experiment 2

The targets in Experiment 1 moved horizontally, and so the direction of implied gravitational attraction was always orthogonal to the direction of target motion. Thus, effects of target size on downward displacement could have resulted from effects that either (a) operate only along the axis aligned with the direction of implied gravitational attraction or (b) are unique to the axis orthogonal to target motion and thus are unrelated to the direction of implied gravitational attraction per se. To distinguish between these alternatives, in Experiment 2 observers saw vertically moving targets. If effects of target size on downward displacement in Experiment 1 were due to effects of an analogue of weight or to other variables specific to the axis aligned with the direction of implied gravitational attraction, then target size should influence displacement along the axis of motion and not along the orthogonal axis. If effects of target size on downward displacement in Experiment 1 were due to characteristics unique to the axis orthogonal to motion, then target size should influence displacement along the orthogonal axis and not along the axis of motion.

Method

Participants. The observers were 12 undergraduates from the same participant pool used in Experiment 1, and none of the observers had participated in the previous experiment.

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

Stimuli. The stimuli were the same as in Experiment 1, with the following exceptions: On each trial, the target either (a) emerged from the approximate midpoint of the top edge of the screen and moved downward or (b) emerged from the approximate midpoint of the bottom edge of the screen and moved upward. The target crossed approximately half of the vertical extent of the screen before it vanished without warning. Each participant received 240 trials (2 directions × 3 velocities × 5 sizes × 8 replications) in a different random order.

Procedure. The procedure was the same as in Experiment 1, with the exception that 1 s after observers initiated a trial by pressing a designated key, the target either (a) emerged from the top edge of the screen and moved downward or (b) emerged from the bottom edge of the screen and moved upward.

Results

M and O displacements were calculated as in Experiment 1, with the following exceptions: M displacement was measured along the y-axis, and O displacement was measured along the x-axis. Positively signed M displacements indicate judged vanishing points beyond the true vanishing point (i.e., below a descending target, above an ascending target), and negatively signed M displacements indicate judged vanishing points behind the true vanishing point (i.e., above a descending target, below an ascending target). Positively signed O displacements indicate judged vanishing points to the right of the true vanishing point, and negatively signed O displacements indicate judged vanishing points to the left of the true vanishing point.

M displacement. The M displacement scores were analyzed with a 2 (direction) × 3 (velocity) × 5 (size) repeated measures ANOVA and are displayed in Figure 2. Size significantly influenced M displacement, $F(4, 36) = 3.84$, $MSE = 25.70$, $p < .02$; a post hoc Newman–Keuls test ($p < .05$) revealed that the 60-pixel ($M = 5.31$) target produced greater M displacement than the 20-pixel ($M = 1.96$) target, and neither the 60-pixel target nor the 20-pixel target were significantly different from the 50-pixel ($M = 4.08$), 40-pixel ($M = 3.74$), or 30-pixel ($M = 3.19$) targets. Interpretation of the size effect must be tempered, though, by a highly significant Size × Direction interaction, $F(4, 36) = 15.88$, $MSE = 36.00$, $p < .001$. As shown in Figure 2, the increases in forward displacement with increases in target size occurred primarily for descending motion; indeed, for ascending motion, increases in target size led to a slight decrease in forward M displacement. There were nonsignificant trends for increases in velocity to produce larger M displacements, $F(2, 18) = 2.05$, $MSE = 71.56$, $p = .15$, and for descending motion to produce larger displacements than ascending motion, $F(1, 9) = 2.66$, $MSE = 853.01$, $p = .14$, and these trends are consistent with previous findings. No other variables approached significance.

O displacement. The O displacement scores were analyzed with a 2 (direction) × 3 (velocity) × 5 (size) repeated measures ANOVA and are displayed in Figure 2. Size did not influence O displacement, $F(4, 36) = 0.94$, $MSE = 9.22$, $p > .45$, nor were any other variables significant.

Discussion

Target size influenced M displacement, but target size did not influence O displacement. These data, in conjunction with the data from Experiment 1 and from Hubbard's (1995a) article, are consistent with the hypothesis that effects of target size and implied mass are observed only along the axis aligned with the direction of implied gravitational attraction. Although the limiting of effects of target size to the axis aligned with implied gravitational attraction did not appear to depend on the direction of target motion, the effects of target size did depend on whether the target was ascending or descending. Larger targets exhibited larger forward displacements for descending motion and smaller forward displacements for ascending motion; larger displacements for larger descending targets might have resulted from effects of weight and momentum acting in the same direction, whereas smaller displacements for larger ascending targets might have resulted from effects of weight and momentum acting in opposite directions and partially canceling out.

Experiment 3

In Experiments 1 and 2, the effect of target size on memory for a moving target was examined, and in each experiment target size influenced displacement along the axis aligned with the direction of implied gravitational attraction. The principles of physical gravitation apply to stationary physical objects as well as to moving physical objects, and so it could be predicted that target size should also influence displacement along the axis of implied

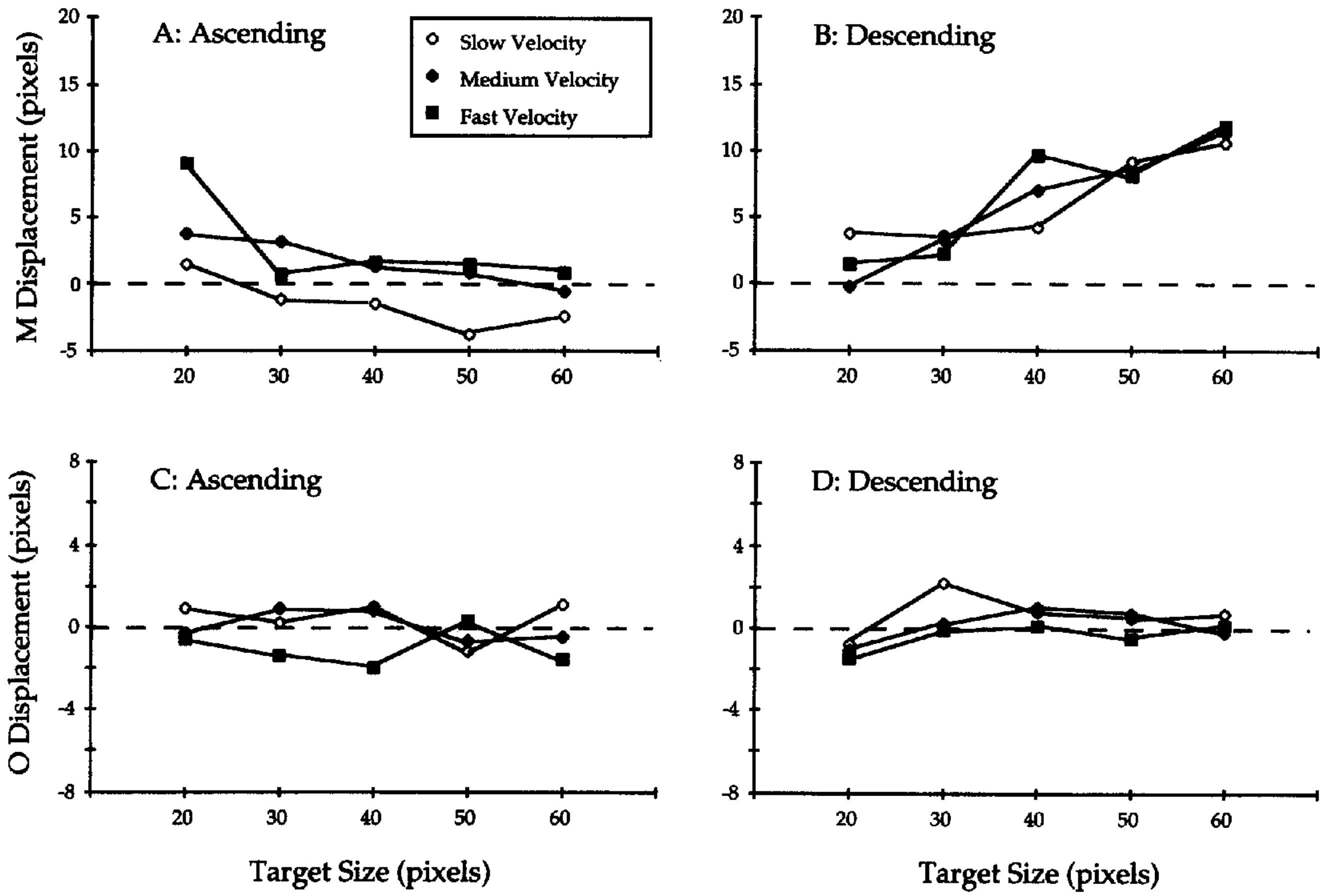

Figure 2. Displacement as a function of target size in Experiment 2. A and B: M displacement data; C and D: O displacement data. A and C: data for ascending targets; B and D: data for descending targets.

gravitational attraction for stationary targets.[2] Previous studies have shown that memory for the location of a stationary target is displaced in ways consistent with the direction of implied gravitational attraction (e.g., Bertamini, 1993; Freyd, Pantzer, & Cheng, 1988), but those studies did not examine the effect of target size on displacement. In Experiment 3, observers were presented with stationary, ascending, or descending targets. If observers' representations include an analogue of weight, then larger stationary targets might exhibit greater downward displacement than smaller stationary targets. On the basis of the results of Experiment 2, it could also be predicted that larger targets would produce greater displacement for descending motion and smaller displacement for ascending motion.

Method

Participants. The observers were 14 undergraduates drawn from the same participant pool used in Experiment 1, and none of the observers had participated in the previous experiments.

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

Stimuli. The target stimuli were the same as in Experiment 2, with the following exceptions: On each trial, the target measured 20, 40, 60, 80, 100, or 120 pixels (approximately 0.83°, 1.67°, 2.50°, 3.33°, 4.17°, or 5.00°) along each side. A stationary condition was added. On stationary trials, the target appeared near the center of the screen and remained visible for 500 ms. On ascending and descending trials, the target was shifted 2 pixels between successive presentations, thus resulting in an apparent velocity of approximately 5°/s; this velocity was equivalent to the medium velocity in Experiments 1 and 2. Each participant received 288 trials (3 directions × 6 sizes × 16 replications) in a different random order.

Procedure. The procedure was the same as in Experiment 1, with the following exceptions: On stationary trials, the target appeared near the center of the screen. On descending trials, the target emerged from the top edge of the screen and moved downward, and on ascending trials, the target emerged from the bottom edge of the screen and moved upward.

[2] Such a prediction is based on the naive physics notion that more massive physical objects fall faster than less massive physical objects, a pattern consistent with the data from Experiments 1 and 2. Such a prediction would not be made from a consideration of the principles of physics, because physical principles clearly specify that all physical objects, regardless of mass, fall at the same rate of acceleration.

Results

The difference between the true vanishing point and the judged vanishing point along the *y*-axis was calculated for each target, and this difference was referred to as *Y displacement.* For stationary targets, positively signed Y displacements indicate judged vanishing points above the true vanishing point, and negatively signed Y displacements indicate judged vanishing points below the true vanishing point. For descending and ascending targets, positively signed Y displacements indicate judged vanishing points beyond the true vanishing point (i.e., below a descending target, above an ascending target), and negatively signed Y displacements indicate judged vanishing points behind the true vanishing point (i.e., above a descending target, below an ascending target).

The Y displacement scores were analyzed with a 3 (direction) × 6 (size) repeated measures ANOVA and are displayed in Figure 3. Direction influenced Y displacement, $F(2, 26) = 4.80$, $MSE = 1{,}134.42$, $p < .02$; a post hoc Newman–Keuls test ($p < .05$) revealed that descending ($M = 15.59$) and ascending ($M = 12.44$) targets produced greater Y displacement than stationary ($M = -0.35$) targets. Interpretation of the direction effect must be tempered, though, by a highly significant Size × Direction interaction, $F(10, 130) = 4.97$, $MSE = 50.54$, $p < .01$; as shown in Figure 3, larger targets produced greater forward displacement for descending motion and produced smaller forward displacement for ascending motion, and target size did not systematically influence downward displacement for stationary targets. Size was not significant, $F(5, 65) = 0.43$, $MSE = 79.29$, $p > .82$.

Discussion

Target size influenced the displacement of moving targets; larger targets produced greater forward displacement when targets descended and smaller forward displacement when targets ascended, and these patterns are consistent with the data from Experiment 2. However, target size did not influence the displacement of stationary targets, nor did stationary targets appear to exhibit significant downward displacement. Why might target size have influenced the displacement of moving targets but not the displacement of stationary targets? One possible explanation is that judgments of vanishing points may have been easier for stationary targets than for moving targets. For moving targets, vanishing-point information was available only just before the target vanished, whereas for stationary targets, vanishing-point information was available during the entire presentation of the target. The longer availability of vanishing-point information for stationary targets may have allowed more attention to be allocated to the encoding of the location of the vanishing point, thus possibly accounting both for the failure of target size to influence displacement and for the apparent lack of any significant downward displacement.

An alternative explanation for why target size influenced judgments of moving targets but not judgments of stationary targets is that observers may have perceived moving targets as requiring continuous effort or work to maintain motion, whereas observers may have perceived stationary targets as not requiring continuous effort or work to maintain position. Experience with physical objects may have shaped the representational system to incorporate the information that (a) a moving object will eventually slow down (because of friction) unless compensatory effort is applied, and (b) no such compensatory effort is required to maintain the position of a stationary object that is otherwise undisturbed. Although such notions are not physically correct, the vast majority of human experience has not involved the ideal and frictionless environment characterized by Newton's laws and in which an object in motion continues in motion; within the terrestrial environment, moving objects require continuous effort to maintain motion, and objects at rest generally remain at rest unless some force is directed toward them (or some supporting force is removed). Indeed, effects of weight may be most noticeable when effort or work is expended to move or lift some object, and therefore, the extent to which implied weight influences the representation may depend in

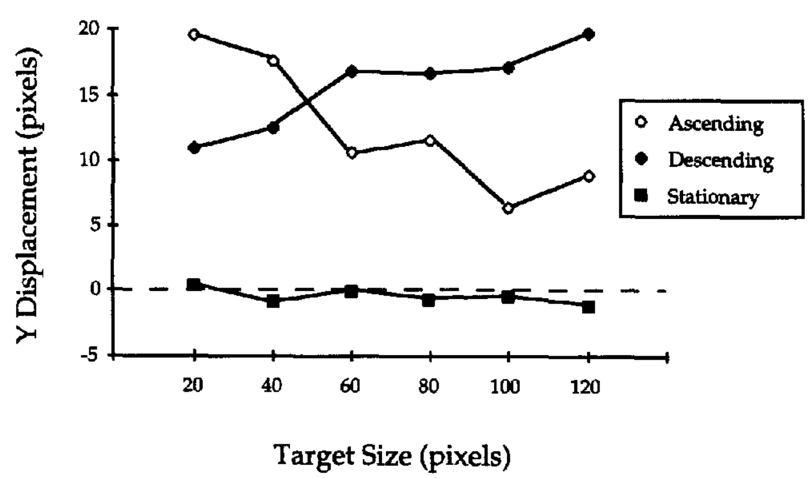

Figure 3. Displacement as a function of target size in Experiment 3.

part on the extent to which observers perceive that effort or work is needed to maintain target motion or position.

Experiment 4

To have more confidence in the notion that observers' representations were sensitive to the implied mass of the target and incorporated an analogue of weight, it was necessary to assess whether observers perceived the larger targets as more massive and heavier than the smaller targets. To have more confidence in the notion that the effect of implied weight depended on the extent to which effort or work was required to maintain the target's motion or position, it was necessary to assess the amount of work or effort observers believed was required to maintain the motion of a moving target or the position of a stationary target. Accordingly, in Experiment 4 observers were shown targets that varied in size and motion across trials and, after viewing each target, judged the mass and heaviness of the target and also judged the effort required to maintain that target in motion (if the target had been in motion) or in position (if the target had been stationary). If changes in target size imply changes in mass and weight, then larger targets should be judged as more massive and heavier than smaller targets. If changes in target size imply changes in the effort needed to maintain motion, then (a) larger targets should be judged as requiring more effort than smaller targets, (b) moving targets should be judged as requiring more effort than stationary targets, and (c) ascending targets should be judged as requiring more effort than descending targets.

Method

Participants. The observers were 13 undergraduates drawn from the same participant pool used in Experiment 1, and none of the observers had participated in the previous experiments.

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

Stimuli. The target stimuli were the same as in Experiment 3, with the following exceptions: Conditions of rightward and leftward motion were added. On rightward trials, the target emerged from the approximate midpoint of the left edge of the screen and moved toward the right; on leftward trials, the target emerged from the approximate midpoint of the right edge of the screen and moved toward the left. On rightward and leftward trials, the target crossed approximately half of the horizontal extent of the screen and then vanished. On rightward and leftward trials, the target was shifted 2 pixels between successive presentations, thus resulting in an apparent velocity of approximately 5°/s; this velocity was the same as that of the ascending and descending targets. Each participant received 60 trials (5 directions × 6 sizes × 2 replications) in a different random order.

Procedure. The procedure was the same as in Experiment 3, with the following exceptions: Rightward trials were included in which the target emerged from the left edge of the screen and moved toward the right, and leftward trials were included in which the target emerged from the right edge of the screen and moved toward the left. After the target vanished, observers were asked to rate on a 1–7 scale (with 1 labeled *not massive* and 7 labeled *very massive*) how massive the target appeared. After observers entered their judgment of mass, they were asked to rate on a 1–7 scale (with 1 labeled *not heavy* and 7 labeled *very heavy*) how heavy the target appeared; after observers entered their judgment of heaviness, they were asked to rate on a 1–7 scale (with 1 labeled *not much* and 7 labeled *very much*) how much work or effort would it take to keep the target in motion (for moving targets) or stationary (for stationary targets).

Results

Because interval differences on the mass, heaviness, and effort scales may not have been perceptually equivalent, the different measures were analyzed in separate 5 (direction) × 6 (size) repeated measures ANOVAs, and the average ratings for each of these measures are displayed in Figure 4.

Mass. Larger targets were rated as more massive than smaller targets, $F(5, 60) = 456.66$, $MSE = 0.54$, $p < .001$, and a post hoc Newman–Keuls test ($p < .05$) revealed that all pairwise comparisons between the 20-pixel ($M = 1.08$), 40-pixel ($M = 2.49$), 60-pixel ($M = 3.41$), 80-pixel ($M = 4.29$), 100-pixel ($M = 5.37$), and 120-pixel ($M = 6.48$) targets were significant. Neither direction nor the Direction × Size interaction was significant.

Weight. Larger targets were rated as heavier than smaller targets, $F(5, 60) = 336.15$, $MSE = 0.61$, $p < .001$, and a post hoc Newman–Keuls test ($p < .05$) revealed that all pairwise comparisons between the 20-pixel ($M = 1.21$), 40-pixel ($M = 2.36$), 60-pixel ($M = 3.21$), 80-pixel ($M = 4.07$), 100-pixel ($M = 5.08$), and 120-pixel ($M = 6.04$) targets were significant. Neither direction nor the Direction × Size interaction was significant.

Effort. Larger targets were rated as requiring more effort to maintain than smaller targets, $F(5, 60) = 141.28$, $MSE = 1.21$, $p < .001$, and a post hoc Newman–Keuls test ($p < .05$) revealed that all pairwise comparisons between the 20-pixel ($M = 1.31$), 40-pixel ($M = 2.39$), 60-pixel ($M = 3.12$), 80-pixel ($M = 3.95$), 100-pixel ($M = 4.86$), and 120-pixel ($M = 5.72$) targets were significant. Direction also influenced ratings of effort, $F(4, 48) = 2.98$, $MSE = 3.31$, $p < .03$; a post hoc Newman–Keuls test ($p < .05$) revealed that descending ($M = 3.00$) targets were rated as requiring less effort to maintain than ascending ($M = 4.00$) targets, and no other pairwise comparisons involving stationary ($M = 3.56$), leftward ($M = 3.60$), or rightward ($M = 3.62$) targets were significant. Size also interacted with direction, $F(20, 240) = 1.69$, $MSE = 0.39$, $p < .03$, and inspection of Figure 4C suggests that this is due to increases in the differences in rated effort between ascending and descending motion for the largest targets and to slightly slower increases in rated effort for stationary targets with increases in target size.

Discussion

Ratings of target mass and target heaviness increased as target size increased, and these patterns suggest that observers are sensitive to the implied mass and weight of computer-animated targets and to changes in the implied mass and weight of those targets as a function of the targets' two-dimensional surface areas. These data offer a valuable manipulation check on the use of changes in target size to imply changes in target mass and weight and are consistent

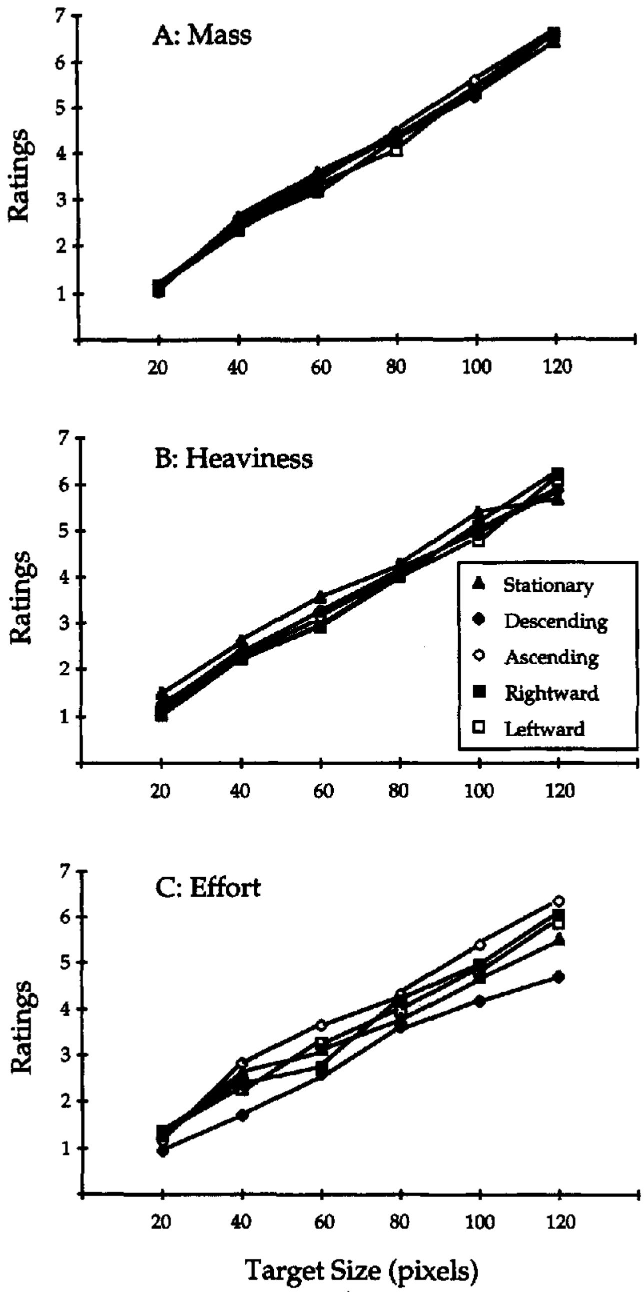

Figure 4. Ratings of mass, heaviness, and effort as a function of target size in Experiment 4. A: ratings of mass; B: ratings of heaviness; C: ratings of effort.

with the claim that observers in Experiments 1, 2, and 3 perceived the larger targets as more massive and heavier than the smaller targets. The ratings are also consistent with previous data on the size–weight illusion (e.g., Koseleff, 1957).

Ratings of the effort required to maintain target motion or position increased with increases in target size. Direction of target motion also influenced ratings of effort, as ascending targets were rated as requiring more effort to maintain than descending targets, and increases in rated effort with increases in target size were slightly larger for ascending targets than for descending targets. These patterns are consistent with effects of implied gravitational attraction; ascending targets move in the direction opposite to implied gravitational attraction, and so effects of weight (and effort to counteract that weight) would be more strongly felt than if motion were in the direction of implied gravitational attraction. These data, in conjunction with the data from Experiment 3, are consistent with the hypothesis that effects of target size and implied weight may be related to the effort or work that would be required to maintain the motion of the target. The ratings of effort for stationary targets increased with target size and did not differ from the averaged rating of effort for moving targets; the increases in ratings for stationary targets may have occurred because stationary targets did not have a clear base of support, and so observers may have perceived stationary targets as requiring some effort to maintain position (i.e., not drop or fall).[3]

General Discussion

Memory for the location of a moving target was influenced by the size of the target, but effects of target size were observed only along the axis aligned with the direction of implied gravitational attraction. Larger horizontally moving targets exhibited greater downward displacement than smaller horizontally moving targets; larger descending targets exhibited greater forward displacement than smaller descending targets, and larger ascending targets exhibited smaller forward displacement than smaller ascending targets. Memory for the location of a stationary target was not influenced by the size of the target. These data are not consistent with the hypothesis that representational momentum results solely from an internalization of the laws of momentum. Instead, these data are consistent with the existence of a separate representational principle—that of representational gravity. Although the existence of representational gravity has been discussed before (see Hubbard, 1995b), the data reported here offer the first empirical evidence that representational gravity may reflect an analogue of weight and not just a constant distortion in the direction of gravitational attraction per se.

The data are consistent with the hypothesis that effects of implied mass have been incorporated into observers' representations as effects of implied weight, because both effects of target size on displacement and effects of physical weight are observed only along the axis aligned with the direction of

[3] If the lack of a clear base of support did contribute to perceived effort, then such effort might counteract the normal downward displacement that would otherwise accompany a stationary object. In Freyd et al.'s (1988) study, the targets had a clear base of support; no effort to maintain the target would have been necessary, and a general downward displacement was observed. In Experiment 3, the stationary targets did not have a clear base of support; effort to maintain the target would have been necessary, and a general downward displacement was not observed. Although clearly speculative, such a comparison suggests that a perceived base of support may be important, and the importance and role of a base of support remains an area for future investigation.

implied gravitational attraction. Furthermore, the influence of implied weight on displacement may be related to whether the observer perceives the weight of the stimulus as a force that needs to be overcome to maintain target motion or position. The notion that weight, and the work or effort associated with overcoming a target's weight, influences displacement suggests that displacement may have a kinesthetic component. Indeed, the hypotheses proposed here involving the importance of weight and effort are consistent with a "motor theory of representation" in which nonvisual weight may be critically important in the determination of the displacement of a visual target. The hypothesis that mental representation may include an analogue of weight is consistent with findings that experimental participants take longer to imagine traversing a given distance if they imagine themselves carrying a heavy object than if they imagine themselves carrying a light object (Intons-Peterson & Roskos-Ewoldsen, 1989), and is also consistent with findings that observers who view visual displays in which another person lifts a box can estimate the weight being lifted (Bingham, 1987; Runeson & Frykholm, 1981, 1983).

The patterns of displacement in Experiments 1, 2, and 3 may be accounted for by a combination of representational gravity (i.e., effects of implied weight) and representational momentum. For vertically moving targets, increases in target weight that would accompany larger target sizes are added to (for descending targets, because representational momentum and representational gravity operate in the same direction) or subtracted from (for ascending targets, because representational momentum and representational gravity operate in opposite directions) the representational momentum of the target to produce the ultimate displacement for that target.[4] For horizontally moving targets, representational momentum and representational gravity occur along separate axes; thus, forward displacement is influenced by representational momentum but not by target size, whereas downward displacement is influenced by target size but not by representational momentum. For stationary targets, increases in target weight that would accompany increases in target size are not as salient; after all, if the weight of a stationary target was not sufficiently supported, the target would not be stationary—it would be falling. Thus, with stationary targets, effects of target weight do not influence the magnitude of downward displacement, and of course, stationary targets by definition possess zero momentum and so are not influenced by representational momentum.

The data are consistent with the claim that effects of target size and implied mass on memory for the location of a moving target are observed only along the axis aligned with the direction of implied gravitational attraction. This pattern does not support the momentum metaphor, but it does support the hypothesis that observers' representational systems incorporate an analogue of weight. Effects of mass are experienced as effects of weight, and so the incorporation of an analogue of weight into the representational system further suggests that the representational system may not incorporate literal physical principles into the representation; rather, the representational system may incorporate the subjective or experiential aspects of those physical principles. Given that the vast majority of human experience has been within the terrestrial setting in which the effects of mass are subjectively experienced as weight, an incorporation of the effects of weight may be more evolutionarily adaptive or useful than an incorporation of the effects of mass per se. The incorporation of an analogue of weight into the representational system and the combination of weight with other types of displacement (e.g., representational momentum) is also consistent with a general framework suggesting that aspects of invariant principles have become incorporated in our representational system.

[4] Although target size influences displacement along the axis of motion for vertically moving targets, target size does not influence representational momentum per se for vertically moving targets; rather, effects of weight are combined with effects of momentum to produce the ultimate displacement.

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