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A Principal Components Analysis of Dynamic Spatial Memory Biases

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Research has shown that spatial memory for moving targets is often biased in the direction of implied momentum and implied gravity, suggesting that representations of the subjective experiences of these physical principles contribute to such biases. The present study examined the association between these spatial memory biases. Observers viewed targets that moved horizontally from left to right before disappearing or viewed briefly shown stationary targets. After a target disappeared, observers indicated the vanishing position of the target. Principal components analysis revealed that biases along the horizontal axis of motion loaded on separate components from biases along the vertical axis orthogonal to motion. The findings support the hypothesis that implied momentum and implied gravity biases have unique influences on spatial memory.

Keywords: memory biases, spatial memory, representational momentum, representational gravity, internalized physical principles

Research has provided evidence of memory biases for a variety of events (see Roediger, 1996), for example, memory biases for events depicted in photographs (e.g., Freyd, 1983; Intraub, Bender, & Mangels, 1992), video clips (Loftus & Palmer, 1974; Thornton & Hayes, 2004), and stories (Bartlett, 1932; Tversky & Marsh, 2000). Particularly relevant to the current study, memory for a target location is often biased in ways generally consistent with the consequences of various physical influences operating on that target. Such findings have led to the hypothesis that representations of subjective experiences of physical principles affect memory (see Hubbard, 1995, 2005).

Several studies have provided converging evidence for this hypothesis. One finding is that memory for the location of moving or implied moving targets is often biased in the direction of implied momentum. For example, after studying a single still picture from a longer motion sequence, such as a person leaping off of a wall, observers took longer to reject as different probe pictures sampled from further along the motion sequence than probe pictures sampled from earlier in the sequence (e.g., Freyd, 1983). Additionally, after viewing sequential presentations implying the rotation of a target, observers tended to misjudge a probe presented further along the implied rotation path as being at the same orientation as the final presentation of the target (e.g., Freyd & Finke, 1984). Further, after viewing a horizontally or vertically translating target that disappeared without warning, observers tended to position a marker beyond the vanishing point when attempting to mark where the target disappeared (e.g., Hubbard & Bharucha, 1988). Freyd and Finke (1984) coined the term *representational momentum* to refer to such spatial memory biases in the direction of implied momentum, arguing that the biases demonstrated the influence of internalized physical principles of momentum on spatial memory.

Since the publication of Freyd and Finke's seminal work on representational momentum (Finke & Freyd, 1985; Freyd & Finke, 1984), research has revealed other biases consistent with the broader hypothesis that representations of subjective experiences of physical principles affect memory (see Hubbard, 1995, 2005). One such finding is that memory for the location of a target is often biased in the direction of implied gravity. For example, after viewing a drawing of a flowerpot hanging by a hook or resting on a table and then viewing a drawing of the flowerpot without the support, observers tended to misjudge a probe flowerpot appearing lower in the display as being at the same height as the originally viewed flowerpot (Freyd, Pantzer, & Cheng, 1988). Additionally, after viewing a horizontally or vertically translating target that disappeared without warning and then attempting to indicate the vanishing point, observers tended to position a marker below the vanishing point for a horizontally translating target and further beyond the vanishing point for downward versus upward translating targets (Hubbard, 1990; Hubbard & Bharucha, 1988). Hubbard (1995, 1997) coined the term *representational gravity* to refer to such spatial memory biases in the direction of implied gravity.

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Hubbard (1995) proposed that representational momentum and representational gravity constitute unique vectors of influence on memory. In Hubbard and Bharucha's (1988) work, for example, representational momentum and representational gravity were hypothesized to operate in the same direction for descending targets, producing relatively large memory displacements in the direction of motion. They were hypothesized to operate in opposite directions for ascending targets, partially canceling their relative influences on spatial memory and producing relatively small forward memory displacements. Furthermore, they were hypothesized to operate in orthogonal directions for horizontally translating targets, producing forward memory displacements in the direction of motion and downward memory displacements in a direction orthogonal to motion (i.e., producing a downward curving trajectory).

If representational momentum and representational gravity indeed provide unique vectors of influence on spatial memory, then measures of their effects should be uncorrelated. To test this hypothesis, we used principal components analysis (PCA) in the present study to examine the latent component structure of measures of representational momentum and representational gravity. If representational momentum and representational gravity provide unique influences on spatial memory, then measures of their influences should load on separate principal components.

As in previous studies of representational momentum and representational gravity (see Hubbard, 1995, 2005), observers in the present study judged the vanishing positions of computer-animated moving targets. The targets moved from left to right and vanished without warning; after a target vanished, observers indicated the vanishing position. Representational momentum was assessed by examining judgment biases along the horizontal axis of motion, and representational gravity was assessed by examining judgment biases along the vertical axis orthogonal to motion.

To examine the generalization of the effects, we used two types of responses. Previous studies have reported equivalent mean displacement patterns between touch screen and trackball or computer mouse responses (Ashida, 2004; Kerzel, 2003; with the exception of finding that pointing without being able to see one's arm and hand movement led to greater displacement along the axis of motion than did pointing while being able to see one's arm and hand movement). Thus, previous findings suggest that touch screen and trackball responses, both being visuomotor responses, should lead to relatively comparable displacement patterns. Additionally, for partial discriminant validation, judgments of the vanishing positions of briefly flashed stationary targets were collected as *nonimplied momentum* condition comparisons.

Method

Participants

Thirty-seven right-handed observers from the undergraduate participant pool at Texas Christian University participated for partial course credit. Each session lasted approximately 1.5 hr.

Apparatus

Each observer sat in a darkened room in front of a computer workstation. A chinrest was positioned 45 cm from a touch screen monitor (Microtouch Studioworks 575N, LG Electronics, Englewood Cliffs, New Jersey; 640 × 480 pixel configuration; 27.2 × 21.6 cm) and aligned 13.5 cm to the left of center of the monitor. A trackball was positioned in front of and to the right of the monitor.

Stimuli

Targets were black circles (radius = 10 pixels; 0.425 cm), and they appeared on a white background. Trials were run in six blocks: two calibration blocks and four test blocks. There were separate blocks of calibration trials for the touch screen and trackball response types, and there were separate blocks of test trials for the touch screen–moving target, touch screen–static target, trackball–moving target, and trackball–static target response type and target activity combinations. On calibration trials, a target appeared at one of five locations (204, 281, 358, 435, or 512 pixels) from the left edge and about midway from the top of the screen (centered at 230 pixels from the top), and the target remained visible until the observer entered a judgment. On touch screen calibration trials, the observer touched the perceived center of the target with the right index finger. On trackball calibration trials, the observer moved the trackball with the right thumb to position crosshairs over the perceived center of the target and pressed a button on the trackball to enter the judgment. The crosshairs initially appeared at a random location at a radius of 20 pixels from the center of the target.

On test trials, an asterisk initially appeared 50 pixels from the left edge of the screen (13.5 cm to the left of center of the monitor, at eye level directly in front of the observer) and remained on the screen throughout the trial. For static target trials, the target appeared at one of five locations (154, 231, 308, 385, or 462 pixels, the identical screen coordinate locations used for targets in the calibration trials) from the asterisk for approximately 757 ms and then disappeared. For moving target trials, the target appeared 70 pixels from the asterisk after approximately 543 ms, moved 70 pixels/s (1 pixel/vertical retrace ≈ 1 pixel/14 ms) to one of five locations (154, 231, 308, 385, and 462 pixels) from the asterisk and then disappeared.

Procedure

Calibration blocks. Calibration blocks preceded the test blocks. For the calibration trials, a target appeared and remained on the screen until the observer entered a response. For both touch screen and trackball calibration trials, the target disappeared after the observer entered a judgment, and the observer pressed a button on the trackball to advance to the next trial. Each calibration block consisted of 50 randomly ordered trials (10 at each distance), preceded by 10 practice trials randomly selected from the 50 trials. The calibration block order was counterbalanced between observers.

Test blocks. Within each of the four test blocks, response type and target activity were held constant (varying only across the blocks) and five target distances were used. On each trial, an asterisk initially appeared. On static trials, the target appeared at one of five distances and then disappeared; on moving trials, the target appeared near the asterisk, moved to the right to one of five distances, and then disappeared. On touch screen trials, the observer kept the right hand on the trackball until the target disappeared, pressed a button on the trackball after the target disappeared, touched the asterisk with the right index finger, and finally touched the remembered target location with the right index finger. On trackball trials, the observer pressed a button on the trackball to make the crosshairs appear after the target disappeared. The crosshairs appeared at a random location at a radius of 20 pixels from the center of the asterisk. The observer then used the right thumb to move the trackball and thereby move the crosshairs over the asterisk, pressed a button on the trackball, used the right thumb to move the crosshairs over the remembered final position, and pressed a button on the trackball to record the judgment.

In previous representational momentum studies using cursor positioning, the cursor appeared at a random location on the screen after the target disappeared. Thus, participants potentially had to shift their attention from the remembered target position to locate the cursor before moving it to the remembered target position. With touch screen responses, however, such an attention shift would not occur. Thus, the requirement to touch or place the cursor over the asterisk was included in the present study to elicit an attention shift in both the trackball and the touch screen trials.

Each test block consisted of 50 randomly ordered trials (10 at each distance) preceded by 10 practice trials randomly selected from the 50 trials. The test block order was counterbalanced between observers on the basis of a Latin square design.

Results

The data from 1 observer who failed to follow instructions were excluded from the analyses. As in previous representational momentum and representational gravity studies that used horizontally translating targets (e.g., Hubbard, 1990), displacement along the axis of motion, or *M displacement*, was calculated as the marked final position along the axis of motion, in pixels, minus the actual final position. Positive values equaled displacement in the direction of implied momentum for moving target trials. M displacement for static trials was calculated in the same way, with a positive difference meaning that the marked position was to the right of the actual final position. For moving and static targets, displacement orthogonal to the axis of motion, or *O displacement*, was calculated as the actual final position along the vertical axis, in pixels, minus the marked final position. Negative values equaled displacement in the direction of implied gravity. Horizontal and vertical calibration values were calculated in the same way as M and O displacement were calculated, respectively.

Displacement and calibration values less than –100 pixels or greater than 100 pixels were considered outliers and deleted (61 of 10,800 responses, or 0.6%; 5 calibration and 56 test trial responses). Then, values less than –2.5 standard deviations or greater than 2.5 standard deviations from the mean per condition (Response Type × Distance conditions for calibration trial values and Response Type × Target Activity × Distance conditions for test trial values) for each observer were considered outliers and deleted (79 of 10,739 responses, or 0.7%; 53 calibration and 26 test trial responses). After deleting the outliers and calculating horizontal and vertical calibration means, we adjusted the observers' Response Type × Target Activity × Distance M and O displacement condition means by subtracting the corresponding mean horizontal and vertical calibration values for each condition (see Table 1 and Figure 1 for the adjusted means).

Overall Displacement Effects

Target Activity (2) × Response Type (2) × Distance (5) repeated-measures analyses of variance were calculated separately for the calibration-adjusted M and O displacement data (see Table 2). The analysis of the M displacement data revealed a significant main effect of target activity. M displacement for moving targets was greater than M displacement for static targets. Additionally, M displacement for moving targets generally was biased in the direction of implied momentum, but memory for static targets generally was not systematically biased. The analysis of the O displacement data revealed a general bias in the direction of implied gravity. Thus, in general, representational momentum and representational gravity effects occurred.

For M displacement, the analyses also revealed significant response type and distance main effects and significant Target Activity × Distance and Response Type × Distance interactions. For O displacement, the analyses also revealed significant response type and distance main effects and a significant Response Type × Distance interaction. The degree of M displacement did vary with distance, but post hoc *t* tests revealed that M displacement was greater for moving targets than for static targets at the 154-, 231-, and 308-pixel distances, all $ts(35) > 3.6$, $ps < .01$. Additionally, post hoc *t* tests revealed that M displacement, averaged across

Table 1
Descriptive Statistics for Target Activity, Response Type, and Distance Displacement Effects

	M displacement		O displacement	
Variable	*M*	95% CI	*M*	95% CI
Target activity				
Moving	5.85	+/−3.35	−3.65	+/−0.98
Static	0.09	+/−2.72	−3.65	+/−0.82
Response type				
Touch screen	4.79	+/−2.76	−5.30	+/−1.29
Trackball	1.15	+/−3.32	−2.00	+/−0.71
Distance (pixels)				
154	−1.07	+/−3.04	−2.70	+/−0.82
231	0.12	+/−3.31	−3.46	+/−0.92
308	6.82	+/−3.45	−3.93	+/−0.95
385	6.85	+/−3.43	−3.71	+/−1.08
462	2.12	+/−3.22	−4.43	+/−1.13

Note. CI = confidence interval.

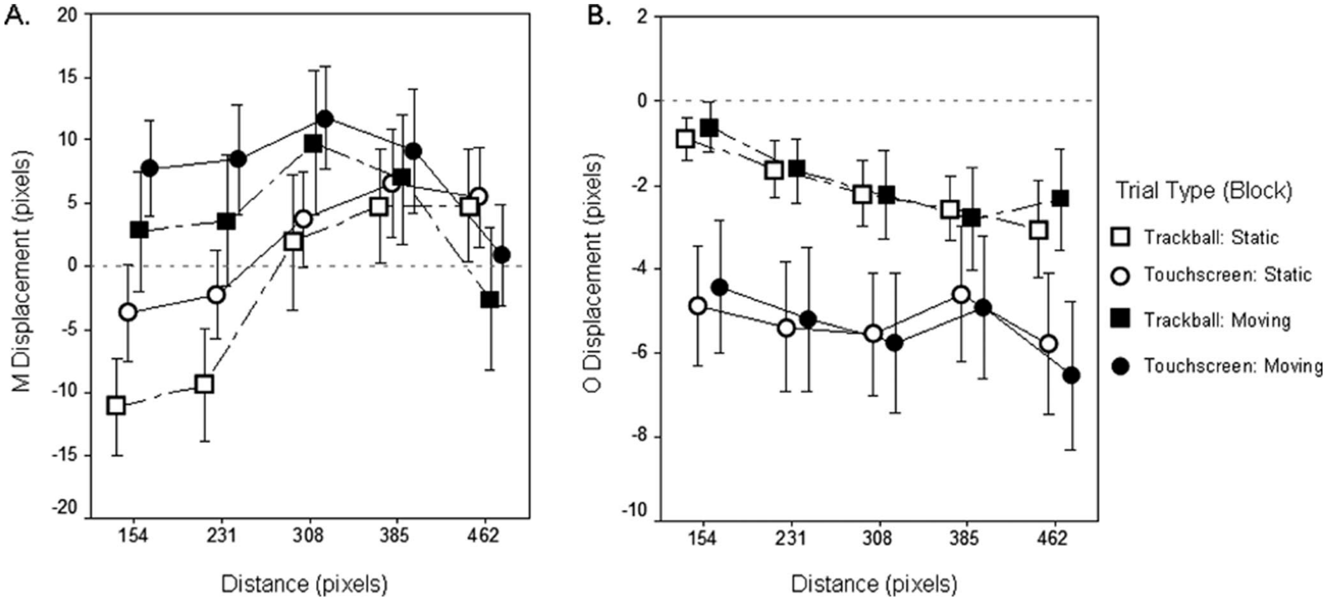

Figure 1. Mean displacement along the axis of motion (M displacement) and displacement orthogonal to the axis of motion (O displacement; A and B, respectively) as functions of target activity, response type, and distance. Circles depict data for touch screen responses, and squares depict data for trackball responses. Filled symbols with solid lines depict data for moving targets, and open symbols with dashed lines depict data for static targets. Bars depict 95% confidence intervals.

target activity, was greater for touch screen than for trackball responses at each distance, all ts(35) > 3.21, ps $< .01$. Finally, the O displacement downward bias generally increased with distance; was greater for touch screen responses than for trackball responses at each distance, all ts(35) > 3.20, ps $< .01$; but did not significantly differ with target activity. The finding that downward displacement in memory for moving targets increased with distance is consistent with effects of gravity on a physical object moving through space; that is, gravity would lead to greater downward movement of the physical object over time. However, in the present study, downward displacement for static targets also increased with distance, even though the presentation time was the same for all target distances. These equivalent downward displacement patterns for moving and static targets then suggest that representational gravity effects on memory may be a function of the time between target disappearance and response programming and execution rather than the distance traversed.

Table 2
Analysis of Variance Summary for Target Activity, Response Type, and Distance Effects

Factor	Result
M displacement	
Target activity	$F(1, 35) = 13.57, p = .001$
Response type	$F(1, 35) = 5.34, p = .027$
Distance	$F(4, 140) = 11.17, p < .001$
Target Activity × Response Type	$F(1, 35) < 1$
Target Activity × Distance	$F(4, 140) = 41.55, p < .001$
Response Type × Distance	$F(4, 140) = 2.53, p = .043$
Target Activity × Response Type × Distance	$F(4, 140) < 1$
O displacement	
Target Activity	$F(1, 35) < 1$
Response Type	$F(1, 35) = 32.85, p < .001$
Distance	$F(4, 140) = 5.72, p < .001$
Target Activity × Response Type	$F(1, 35) < 1$
Target Activity × Distance	$F(4, 140) < 1$
Response Type × Distance	$F(4, 140) = 2.72, p = .032$
Target Activity × Response Type × Distance	$F(4, 140) = 1.25, p = .294$

PCA

PCA (with matrix rows = subjects and columns = M and O displacement measurements per Target Activity × Response Type × Distance conditions) was conducted to examine the relationship between M and O displacement.[1] Varimax rotation was applied for structure simplification and interpretation reliability (Abdi, 2003; Stevens, 1996; oblique promax rotation yielded results similar to those reported below).

Nine components having eigenvalues above 1.00 accounted for 84% of the variance (see Table 3), and all had commonalities greater than .70.[2] Component loadings with absolute values greater than or equal to .60 (in bold in Table 4) were primarily used to

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[1] The correlation matrix used in the PCA is available at http://www.utdallas.edu/research/nprlab/supporting_docs/JEPLMC_PCA_Matrix.pdf.

[2] The most commonly used criterion for the retention of components is to retain those with eigenvalues greater than one. This criterion has been shown to be acceptably accurate when the number of variables is less than 30 and the communalities are greater than .70 (see Stevens, 1996), as in the present study.

Table 3
Eigenvalues and Percentages of Variance Explained for Each Principal Component Both Before and After Varimax Rotation

	Extraction sums of squared loadings		Rotation sums of squared loadings	
Component	Eigenvalue	% of variance	Eigenvalue	% of variance
1	9.91	24.78	6.90	17.25
2	7.16	17.89	6.48	16.21
3	4.06	10.15	4.50	11.26
4	3.19	7.98	4.11	10.29
5	2.75	6.86	3.60	9.01
6	2.25	5.64	2.65	6.63
7	1.55	3.87	2.08	5.20
8	1.37	3.42	1.65	4.11
9	1.26	3.15	1.52	3.80

evaluate each component, but loadings that were less than .60 and greater than .33 also were considered (in italics in Table 4). Component interpretation was based on the strength of the component loadings relative to the ratio of the number of variables examined to the sample size (see Stevens, 1996): For $k = 20$ to $n = 36$, $|r| > .33$ with pairwise $\alpha = .05$, and $|r| \geq .60$ with Bonferroni corrected familywise $\alpha = .05$. Additionally, component reliability was considered on the basis of component saturation and sample size, with components having three loadings greater than or equal to .80 or four loadings greater than or equal to .60 considered reliable regardless of sample size (see Stevens, 1996).

The PCA revealed that M and O displacement measures loaded on separate components, supporting the hypothesis that representational momentum and representational gravity make unique contributions to overall displacement. O displacement exclusively loaded on Components 1, 2, and 7, and M displacement exclusively loaded on Components 3, 4, 5, 6, and 8.[3] In fact, none of the correlations between the M and O displacement measures were significant ($M\ r = -.03$, $Mdn\ r = -.05$, $M\ |r| = .13$, $Mdn\ |r| = .11$; with $\alpha = .05$, $r > .33$ would be considered statistically significant).

PCA also revealed that O displacement consistency varied with response type and that M displacement consistency varied with response type, target activity, and distance. That is, O displacement loaded on separate touch screen and trackball components (Components 1 and 2, respectively; except for the touch screen–static, 385-pixel vanishing point loading). Additionally, M displacement loaded on a separate touch screen, moving target component (Component 4; except for the trackball–moving, 308-pixel vanishing point loading), on separate shorter and longer distances trackball components (Components 3 and 6, respectively), and on separate shorter and longer distances stationary target components (Components 8 and 5, respectively).

Supplementary Analyses of Memory Biases for Moving Targets

In the present study, static targets served, in part, as comparison stimulus conditions to isolate target movement effects from potential distance effects, and research across a variety of psychology subdisciplines has revealed biases in memory for static target distances (e.g., Flanders, Tillery, & Soechtig, 1992; Gentilucci & Negrotti, 1994; Loomis, Da Silva, Fujita, & Fukusima, 1992). In the present study, mean M displacement for static targets did vary with distance. Additionally, M displacement loaded on the static target component (Component 5), and M displacement for static and moving targets loaded on common trackball components (Components 3 and 6). Thus, the data suggest that individual differences in representations of distance affect M displacement for moving targets. Therefore, to examine M displacement for moving targets without the influence of distance biases, we subtracted M displacement for static targets from M displacement for moving targets at corresponding Distance × Response Type conditions (see Figure 2). A Response Type (2) × Distance (5) repeated-measures analysis of variance revealed only a significant effect of distance, $F(4, 140) = 41.55$, $p < .001$. Regardless of the response type, M displacement systematically decreased with target distance, $F_{\text{linear}}(1, 35) = 116.84$, $p < .001$, and $F_{\text{quadratic}}(1, 35) = 13.60$, $p = .001$, similar to previously reported findings of M displacement decreases as a target approaches a boundary (Hubbard & Motes, 2005). However, PCA did reveal that the distance-adjusted M displacement measures loaded on separate touch screen and trackball components (see Table 5). Additionally, the relationships between trackball measures further subdivided into shorter and longer distance components.

Discussion

In the present study, the relationships between dynamic spatial memory biases for moving and static targets were examined. In particular, memory biases hypothesized to result from representational momentum and representational gravity were examined. In general, memory for the moving targets was found to be displaced forward in the direction of implied momentum, and memory for moving and static targets was found to be displaced downward in the direction of implied gravity. Furthermore, memory biases along the axis of implied momentum for moving targets were not correlated with memory biases along the axis of implied gravity for moving or static targets.

Theory and research has suggested that memory displacements overall can be multiply determined (e.g., by characteristics of the target, display, context, and observers; see Hubbard, 2005), that representations of the subjective experiences of physical principles are often a primary influence on such displacements (Hubbard, 2006), and that representational momentum and representational gravity (and other internalized physics principles) constitute unique vectors of influence on such displacements (Hubbard, 1995). The forward and downward biases found in the present study are consistent with previous spatial memory findings and consistent with the hypothesis that representational momentum and representational gravity can bias spatial memory. The novel finding that the forward and downward biases loaded on separate principal components then supports the hypothesis that representational momentum and representational gravity constitute unique vectors of influence on spatial memory.

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[3] Some M and O displacement measurements loaded on the ninth component, and some O displacement measurements loaded on the seventh component. However, these loadings did not meet the component interpretation criteria, and the overall pattern was not systematic.

Table 4
Principal Component Loadings

		Component								
Activity and response	Distance	1	2	3	4	5	6	7	8	9
					M displacement					
Static										
Trackball	154	−0.09	−0.08	***0.70***	−0.18	−0.08	0.22	0.00	*0.42*	0.07
Trackball	231	−0.01	−0.06	***0.67***	−0.04	*0.49*	0.10	0.28	0.02	0.08
Trackball	308	−0.01	−0.15	***0.61***	−0.09	*0.40*	−0.03	−0.06	0.13	*−0.50*
Trackball	385	−0.08	−0.13	0.26	−0.10	***0.61***	*0.52*	0.07	0.05	−0.27
Trackball	462	−0.14	−0.22	−0.09	0.00	0.28	***0.80***	0.05	0.09	0.01
Touch screen	154	−0.23	−0.03	0.18	0.27	*0.40*	0.02	−0.26	***0.66***	−0.01
Touch screen	231	−0.10	−0.18	0.25	0.31	*0.48*	−0.25	0.03	*0.52*	−0.16
Touch screen	308	−0.07	−0.07	0.25	0.23	***0.77***	0.01	−0.03	0.13	−0.18
Touch screen	385	0.07	0.10	0.12	0.21	***0.83***	0.13	0.01	0.09	0.07
Touch screen	462	−0.05	0.06	−0.28	0.07	***0.83***	0.17	0.09	−0.09	0.24
Moving										
Trackball	154	−0.03	0.01	***0.76***	0.21	−0.11	0.21	−0.15	*0.37*	0.00
Trackball	231	−0.05	0.17	***0.87***	0.19	0.11	−0.08	−0.10	−0.04	0.02
Trackball	308	0.11	−0.05	***0.80***	*0.37*	0.05	0.02	−0.11	−0.20	0.03
Trackball	385	0.01	−0.05	*0.54*	0.27	0.16	***0.63***	−0.13	−0.24	−0.18
Trackball	462	−0.09	0.12	0.32	0.32	0.00	***0.73***	−0.18	−0.08	0.17
Touch screen	154	−0.26	0.09	0.32	***0.69***	0.05	−0.06	−0.16	0.18	0.28
Touch screen	231	0.01	0.13	0.33	***0.79***	0.10	−0.14	−0.06	0.11	0.16
Touch screen	308	0.11	0.02	0.09	***0.90***	0.04	0.04	−0.07	−0.04	−0.15
Touch screen	385	0.03	0.22	−0.07	***0.85***	0.22	0.21	0.07	−0.04	−0.09
Touch screen	462	0.09	0.15	−0.02	***0.71***	0.20	0.41	0.14	0.20	0.04
					O displacement					
Static										
Trackball	154	***0.70***	0.24	0.04	0.12	0.19	−0.33	−0.11	−0.23	0.23
Trackball	231	***0.86***	0.05	−0.02	−0.04	−0.03	−0.11	0.02	−0.05	0.21
Trackball	308	***0.72***	0.19	0.17	0.06	0.09	0.06	−0.14	−0.21	*0.49*
Trackball	385	***0.80***	0.17	0.06	−0.09	0.08	0.06	−0.28	−0.03	−0.05
Trackball	462	*0.38*	0.28	0.27	−0.03	−0.02	0.18	***−0.66***	0.12	0.15
Touch screen	154	0.02	***0.63***	0.09	−0.18	0.13	−0.05	*0.55*	−0.02	0.26
Touch screen	231	0.23	***0.68***	0.09	0.01	0.20	0.02	0.20	0.18	*0.46*
Touch screen	308	0.17	***0.81***	0.07	0.08	0.06	−0.24	0.08	−0.07	0.25
Touch screen	385	*0.38*	***0.75***	0.03	0.20	−0.03	−0.07	0.03	−0.10	0.05
Touch screen	462	0.07	***0.82***	0.04	0.13	−0.07	−0.03	*−0.37*	0.05	0.01
Moving										
Trackball	154	***0.80***	0.20	−0.07	0.21	−0.04	−0.25	0.22	−0.11	−0.08
Trackball	231	***0.83***	0.19	−0.24	−0.10	0.09	−0.12	0.17	−0.11	−0.15
Trackball	308	***0.93***	0.08	−0.08	0.04	−0.04	0.11	0.03	−0.03	−0.15
Trackball	385	***0.87***	0.24	−0.03	0.04	−0.15	0.02	0.11	0.12	0.03
Trackball	462	***0.85***	0.23	0.17	−0.02	−0.26	0.04	−0.14	0.19	−0.01
Touch screen	154	0.21	*0.53*	−0.12	−0.05	0.09	0.05	***0.74***	−0.07	0.05
Touch screen	231	0.26	***0.76***	0.02	0.20	−0.09	−0.07	0.22	0.29	0.05
Touch screen	308	0.06	***0.92***	0.00	0.09	0.00	0.01	0.11	−0.15	0.03
Touch screen	385	0.26	***0.83***	−0.10	0.17	0.00	−0.05	−0.01	−0.14	−0.30
Touch screen	462	0.23	***0.81***	−0.13	−0.07	−0.10	0.17	−0.12	0.03	−0.12

Note. Rotation method: Varimax with Kaiser normalization. Rotation converged in 13 iterations. Distance is expressed in pixels. Values in bold have absolute values greater than or equal to .60; values in italics have absolute values less than .60 and greater than .33.

This finding that representational momentum and representational gravity constitute unique vectors of influence on memory has important implications for theories of memory displacements (see Hubbard, in press). The dissociation between representational momentum and representational gravity shows that models of spatial memory distortions and, possibly, models of action programming and execution need to include separate influences of representational momentum and representational gravity. Additionally, the finding of distance influences on forward displacement shows that studies aimed at understanding representational momentum need to consider distance representation biases in the absence of motion. Furthermore, the finding that representational momentum and representational gravity constitute unique vectors of influence on memory suggests unique brain implementations for representational momentum and representational gravity computational influences. Although functional imaging studies have explored representational momentum effects (e.g., Kourtzi & Kanwisher, 2000;

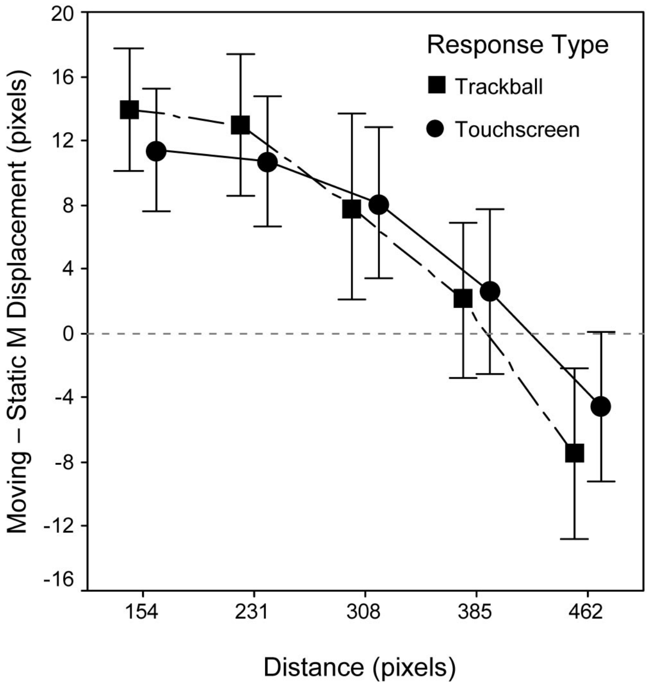

Figure 2. Mean displacement along the axis of motion (M displacement) for moving targets as a function of response type and distance, after subtracting corresponding mean static M displacement values. Circles and solid lines depict data for touch screen responses, and squares and dashed lines depict data for trackball responses. Bars depict 95% confidence intervals.

Rao et al., 2004; Senior, Ward, & David, 2002), representational gravity effects have not been explored.

In the present study, touch screen and trackball responses were included as two convergent methods of assessing representational momentum and representational gravity biases. However, isolable touch screen and trackball downward displacement components and an isolable, touch screen, moving, forward displacement component were discovered. These data show the need to consider contributions of programming and executing specific types of responses (e.g., trackball vs. touch screen in the present study) to memory biases.

The finding that touch screen and trackball responses were associated with different displacement patterns in the present study was unexpected (cf. Ashida, 2004; Kerzel, 2003; Kerzel & Gegenfurtner, 2003; but see Gentilucci & Negrotti, 1994), and aspects of the differences might be explained by referent, topography, or experience differences. That is, the final target positions for touch screen responses ultimately would have to have been referred to the pointing hand (Flanders et al., 1992), but for trackball responses, the motor programming and execution required would have to have been based on the represented distance between the final target position and the cursor position, not the hand operating the trackball. Additionally, motor programming and execution also would have been influenced by the mapping of the movement of the cursor in response to movement of the trackball. As with typical cursor to trackball or mouse mapping, cursor movement was proportionally greater than the inducing trackball movement, and upward and downward movement of the cursor was produced by corresponding forward and backward movement of the trackball in the horizontal plane. Furthermore, we informally observed that typical trackball responses consisted of combinations of relatively fast gross ballistic movements (i.e., moving the cursor toward the asterisk or remembered vanishing position) followed by relatively slow fine movements (i.e., precisely positioning the cursor over the asterisk or over the remembered vanishing position), but typical touch screen responses consisted of two relatively smooth movements that slowed on approach to the screen (i.e., a movement to touch the asterisk and a movement to touch the vanishing point). Finally, the thumb-operated trackball response also was presumably relatively novel to the observers. Thus, any or all of these referent, topography, and experience differences might explain finding the isolated trackball component. However, such differences alone cannot explain the findings that touch screen forward biases for static and moving targets did not load on a common component, that touch screen and trackball forward biases for static targets loaded on a common component, and that touch screen forward biases for moving targets loaded on an isolated component.

Indeed, the data from the present study not only address the motivating hypothesis that representational momentum and representational gravity constitute unique vectors of influence on memory but also raise interesting questions and suggest directions for future research. These questions target several levels of theorizing

Table 5
Principal Component Analysis (PCA) of the M Displacement Data for Moving Targets After Subtracting M Displacement for Static Targets: PCA Loadings With Eigenvalues and Percentages of Variance Explained for Each Principal Component Both Before and After Varimax Rotation

Variable	Component 1	Component 2	Component 3
Trackball response			
Distance (in pixels)			
154	0.21	0.06	***0.78***
231	0.09	*0.36*	***0.76***
308	0.29	***0.84***	0.00
385	0.14	***0.82***	0.25
462	0.06	***0.76***	0.31
Touch screen response			
154	***0.66***	*0.48*	−0.18
231	*0.59*	*0.57*	0.16
308	***0.81***	0.15	*0.39*
385	***0.87***	0.09	0.08
462	***0.66***	0.15	*0.40*
Extraction loading			
Eigenvalue	4.71	1.34	1.18
+% of variance	47.06	13.37	11.78
Rotation loading			
Eigenvalues	2.80	2.68	1.73
% of variance	28.04	26.83	17.35

Note. Rotation method: Varimax with Kaiser normalization. Rotation converged in 7 iterations. Component loadings in bold have absolute values greater than or equal to .60; component loadings in italics have absolute values less than .60 and greater than .33.

(Marr, 1982) about memory displacements (Hubbard, 2005): for example, the orthogonality of other hypothesized internalized physical principles, the separation of brain mechanisms mediating different types of displacement, and the influence of response types on displacement. Furthermore, Hubbard (2005) proposed that memory displacements, like those attributed to representational momentum and representational gravity, serve the goal of bridging processing delays between perception and action, and the present data suggest that this goal is achieved in part by developing relatively orthogonal processes representing the subjective experiences of factors affecting physical objects.

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