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Representational Momentum for a Spiral Path

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When a ball is shot through a spiral tube at high speed, the ball emerges in a straight path tangent to the ball's point of departure from the tube. However, past research has shown that many Ss believe the ball follows a curved pathway. In the 3 experiments described in this article, a ball traveling through a spiral tube was animated on a computer graphics screen. Ss' memory distortions for positions of the ball along each of 3 pathways were measured using a representational momentum paradigm. Retention interval was varied across the 3 experiments. The results from the 3 experiments reported here replicate retention interval results previously reported for representational momentum effects, and they suggest that the representational pathway of a ball exiting a spiral tube is spiral in shape. These findings may shed some light on why people have demonstrated naiveté on the spiral tube problem in past research.

One might expect that either through natural selection or everyday experience, people would have acquired a fairly accurate understanding of how moving objects behave. However, many results from now-classic "naive physics" studies suggest that, if anything, people hold erroneous beliefs about laws of motion. For instance, using tasks such as the "spiral tube" problem, McCloskey, Caramazza, and Green (1980) found that college students frequently report that the trajectory of a moving object will continue to show some curvature even after external forces stop determining a curvilinear path.

McCloskey (1983) suggested that these sorts of errors arise from a systematic, well-developed conception of motion that is inconsistent with the laws of classical physics. McCloskey suggested that the naive belief system appears similar to the medieval theory of impetus. In the spiral tube case, for instance, the ball will have acquired a curvilinear impetus while constrained by the tube.

Although this basic effect (i.e., that many subjects indicate the exiting ball will take a curvilinear path) has been replicated many times, its implications have been challenged (e.g., Kaiser, Proffitt, Whelan, & Hecht, 1992; Proffitt & Gilden, 1989). One challenge is the role of the static, highly conceptual, stimulus display and task. In the original experiments, subjects were shown spiral tubes printed on paper, and they were asked to draw trajectories on the paper. If we assume that perceptual processes are relatively modular (Fodor, 1983), it is not unreasonable to suppose that knowledge of certain physical regularities of motion is available to the representational system underlying perceptual processing and adaptive motor responses but unavailable to the representational system underlying the sort of conscious conceptual understanding of the world necessary to answer explicit questions about physical laws and outcomes (Finke & Freyd, 1989).

Kaiser, Proffitt, and Anderson (1985) hypothesized that the static display might have probed highly conceptualized knowledge, whereas a more dynamic display might elicit more physically accurate knowledge. They compared static with dynamic displays using a curved tube. They found that performance was generally better with the dynamic displays. However, the evidence remains somewhat mixed. Kaiser et al. (1985) showed some improved performance for the motion conditions, but many subjects showed no difference in performance (cf. Kaiser et al., 1992). Also, McCloskey and Kohl (1983) reported that viewers were just as accurate with static displays as with dynamic displays. Furthermore, Shepard (1981, 1984) has argued that the perceptual system does not favor internalized knowledge of dynamics but that instead it relies on rules of kinematic geometry. If so, one might expect that displays that evoke perceptual representations may not necessarily produce more accurate performance on tasks assessing knowledge of dynamic physical laws.

In the research presented here, we turned to a paradigm, representational momentum (Freyd & Finke, 1984), that has previously produced results supporting two relevant conclusions. First, representational momentum is a property of perceptual representations and is fairly immune from higher level cognitive penetration (see Finke & Freyd, 1989; Freyd, 1993). Second, representational momentum is influenced by parameters such as display velocity (Freyd & Finke, 1985; Finke, Freyd, & Shyi, 1986) in a way that is analogous to influences on physical momentum.

These two conditions suggested to us that a representational momentum task involving a spiral tube display might produce evidence that perceptual representations were guided by accurate knowledge of physical laws. In representational momentum experiments, subjects are asked to remember the final position of a depicted object after viewing an inducing

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display implying motion. For instance, in one study (Freyd & Finke, 1985) subjects were presented with a static figure in a sequence of orientations sampled from a possible path of rotation. Subjects were instructed to remember the third orientation they saw and were presented with a fourth orientation that was either the same as or different from the third. Test orientations were varied parametrically around the true–same position. We found a generally symmetric unimodal distribution of "same" responses centered not on true–same but on a forward rotation from true–same. That is, subjects showed a shift in memory for position, and the magnitude of the memory shift was a function of the display velocity (Freyd & Finke, 1985). In subsequent studies, the magnitude of memory shift has been used to investigate the nature of the dynamic mental representation (Bertamini, 1993; Freyd, 1987, 1992, 1993) underlying the momentum effect. For instance, memory shifts vary with object coherence (Kelly & Freyd, 1987); the directionality of the depicted object (Freyd & Miller, 1992; Freyd & Pantzer, in press); the implied acceleration of the inducing display (Finke et al., 1986); and event anticipation (Verfaillie & d'Ydewalle, 1991). We predicted that, similarly, memory shift would vary with the implied path of motion taken by a ball exiting a spiral tube, such that the more physically accurate the motion, the larger the memory shift.

Although our prediction was that the more physically accurate the motion, the larger the memory shift, there is some basis for expecting a different pattern of results. One line of argument is that simple pattern completion or "good continuation" would place the greatest momentum along the spiral path. Alternatively, a curved or spiral path might be expected to dominate under certain perceptual assumptions of animacy (Freyd, 1992; Freyd & Miller, 1992). If humans are especially evolved to process animate motion (Shiffrar & Freyd, 1990, 1993), subjects may attribute (at the perceptual level) internal force to the moving ball, as is the case with animate objects. This internal force would permit the ball to continue to move in a spiral or curved path even after leaving the tube. A third possible reason to expect greater momentum along the spiral path is suggested by the finding that the momentum occurs along a path that is consistent with the inducing display, as reported by Hubbard and Bharucha (1988) and Verfaillie and d'Ydewalle (1991).

Despite these lines of argument that suggest the spiral or curved path may show greater momentum than the straight path, we predicted that the magnitude of the representational momentum would be greatest for the physically correct path. Our prediction was motivated by the findings reviewed above suggesting that representational momentum effects mirror physical momentum. Most recently, Bertamini (1993) reported a new demonstration of the internalization of mechanics using a representational momentum task. Bertamini measured memory distortion for the position of an object on an inclined plane. Angle of inclination was varied, and Bertamini found that the memory shift increased with greater angles of inclination. Findings such as Bertamini's (1993) and Freyd and Finke's (1985) discovery of a velocity effect suggested to us that a representational momentum task involving a spiral tube display might produce evidence that perceptual representations were guided by accurate knowledge of physical laws. We thus predicted that representational momentum would be greatest along the correct straight path exiting the spiral tube.

Experiment 1

In Experiment 1, we used an animated display of a ball shooting through a spiral tube. We varied the exit path of the ball such that it took one of three paths: a curved, spiral, or straight path. Subjects were given instructions about how to interpret the spiral tube and the ball that were based closely on instructions given in classic naive physics experiments using a spiral tube and a pencil-and-paper task. That is, subjects were told to imagine themselves looking down on the spiral tube and to imagine the ball movement as unhampered by gravity or friction. For each of the path conditions, we measured memory for the final position of the ball at a position outside the tube, using a standard representational momentum memory task (e.g., Freyd & Finke, 1985).

We predicted that memory shifts would be more powerfully forward for the straight path than the curved or spiral path. In other words, we expected increased representational momentum effects for the physically correct path. This prediction was based on other studies showing evidence that the magnitude of representational momentum is a function of the perceptual and representational characteristics of the context. For instance, Freyd and Pantzer (in press) discovered that a forward moving arrow produces stronger shifts than a backward moving arrow. Freyd and Miller (1992) reported that a forward moving icon of a "creature" produces stronger shifts than a backward moving icon of a creature. Furthermore, we were guided by the findings that indicate memory shifts are consistent with internalized physics. For instance, Freyd and Finke (1985) reported that memory shift increases with display velocity, and Freyd, Pantzer, and Cheng (1988) found that memory shifts for static displays were consistent with changes expected on the basis of physical forces such as gravity and spring dynamics. Similarly, Hubbard (1990) reported a gravity effect for representational momentum. We thus expected to discover that representational momentum shifts would be greatest for the straight path and lowest or nonexistent for the spiral path, with curved path results intermediate. Indeed, we hoped to show that the naive physics of the perceptual system are superior to that of the cognitive system (Kaiser et al., 1985).

Method

Subjects. We recruited 24 subjects from the University of Oregon community.

Apparatus. Stimuli were presented on a Hewlett-Packard (HP) 1340A vector-plotting display screen, 9.6 cm × 11.9 cm. The display screen was connected by an HP 1351A graphics generator to an HP 9133A microcomputer. The display screen was vertically mounted on a wooden platform approximately 30 cm high; consequently, the center of the vector-plotting screen was at eye level for subjects, who sat at a small table for the duration of the experiment. Subjects used a foot pedal to initiate trials and two separate key presses (one for each hand) to indicate responses. Subjects sat at a comfortable viewing distance from the graphics screen (approximately 50 cm), in a dimly lit laboratory room.

Stimuli and format of trials. At the start of each trial, subjects were presented with a hollow spiral tube displayed in the center of the graphics screen (see Figure 1). The spiral was approximately 4.0 cm by 3.5 cm, and the linear extent of the spiral was approximately 14 cm. When a foot pedal press was initiated by the subject, a ball appeared 7 mm of arc distance from the beginning of the spiral and traveled through the tube. The inducing sequence consisted of eight appearances of the ball inside the tube and a final appearance of the ball outside the tube. Each ball was approximately 19 mm from the next along the implied path. All of the balls remained on the screen for 150 ms each, with an interstimulus interval of 0 ms; the first eight balls appeared within the spiral tube itself (with the last ball appearing at the very end of the tube), and gave the subjective appearance of fairly continuous motion. The ninth ball appeared outside of the tube, and also remained on the screen for 150 ms; it was placed such that it appeared to follow a straight, curved, or spiral path. The inducing sequence was followed by a 150-ms retention interval, during which time the screen was blank and subjects attempted to remember the final position of the ball. A test ball was then presented on the screen. The test ball was either in the same position as the final position of the ball in the first display or in one of four distractor positions. The five test positions were presented equally often in a random order. Two of the test positions were positive displacements (in the direction the ball had been moving) of 0.10 cm and 0.20 cm, and two of the test positions were equally negative displacements. The spiral tube was not presented with the test ball.

Design. Twelve subjects were assigned to a "clockwise" version of the experiment (the spiral tube was curved in the clockwise direction); the other 12 subjects completed a "counterclockwise" version. Each subject completed three blocks of 140 trials each; within each block, the first 20 were always practice trials and the remaining 120 were the analyzed experimental trials. The three blocks corresponded to the possible paths taken by the ball as it exited the spiral tube. In the straight path block, the ball exited the tube along a straight line tangent to the end position of the tube (see Panel A of Figure 1); it traveled a linear distance of 19 mm from the end of the spiral tube. In the spiral path block, the ball exited the tube along a spiral arc equal to the arc of the tube itself (see Panel B of Figure 1); it traveled an arc distance of 19 mm (which corresponded to a shortest line distance of 18.6 mm). In the curved path block, the ball exited the tube along a curved path intermediate between the straight and spiral pathways (see Panel C of Figure 1); it traveled an arc distance of 19 mm (which corresponded to a shortest line distance of 18.8 mm). Test positions lay along the path of the ball defined for each block. Block order was counterbalanced across subjects. Within each block, subjects saw one of four possible exit directions of the ball from the spiral tube; these four exit directions were randomly ordered and were created by having the tube presented at four possible screen orientations so that the ball exited in an upward, downward, leftward, or rightward direction. Figure 1 displays a schematic depiction of a spiral tube from the counterclockwise, leftward condition. (The leftward condition for the clockwise tube would have an exit position at the bottom of the screen.) Finally, there were six replications of each trial for each exit direction for each path block.

Procedure. Subjects were given thorough written and oral instructions. As in previous spiral-tube experiments, subjects were instructed to imagine the tube as made of metal and placed horizontally below them with a metal ball traveling through it. They were told about the structure of individual trials and were instructed to indicate whether the test ball was in exactly the same position as it had been in when it stopped moving and disappeared after exiting the tube. They were instructed to hit the key press marked *same* if they believed the distractor ball was in exactly the same position as the original ball that had disappeared and to strike the key press marked *different* if they believed otherwise. Subjects were told that they should not expect an equal number of same and different trials. Both speed and accuracy were stressed in the instructions. Finally, subjects completed the first block of 20 practice trials while the experimenter was still present; this allowed the experimenter to ensure that the subjects understood the instructions and also allowed the subjects to ask any questions before continuing with the experimental trials. During this time, the experimenter was unaware of the data; in fact, subjects' responses to the practice trials were not even recorded.

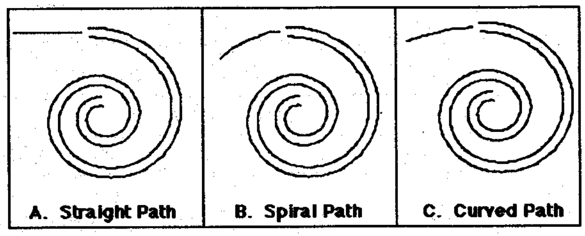

Figure 1. Schematic depictions of the three path conditions used in the experiments. The end point of each path shown above corresponds (approximately) to the true–same position of the ball. The four remaining distractor balls were placed around the true–same position, either forward or backward along the implied trajectory. The spiral tube shown is counterclockwise in its rotation direction, and the exit direction of the emergent ball is leftward; rotation direction and exit direction were counterbalanced across path conditions for all experiments.

Postexperiment questionnaire. Once subjects had completed the computer portion of the experiment, they were given a short questionnaire. The questionnaire was designed to elicit increasingly specific information from the subjects about the explicit knowledge they had brought to bear on the more perceptual computer task. Each question was printed on its own page, and subjects were monitored while they completed the four-page questionnaire to ensure that the questions were answered in the intended order. The four questions assessed the following information from each subject:

1. Did the subject notice a difference between the three blocks of trials?
2. Given a drawing of a spiral tube, each subject was asked to sketch the trajectory of the ball as it would emerge from the spiral tube.
3. Given drawings of the three trajectories actually animated in this experiment, each subject was asked which pathway was the correct one.
4. What was the subject's physics and mathematics background?

After completing the questionnaire, subjects were debriefed and thanked for their participation.

Results and Discussion

We calculated the percentages of same responses for each condition and each subject. We derived a measure of memory shift by calculating a central tendency from the distribution of same responses by test position for each condition. The estimate of shift we used as a dependent measure for inferential hypothesis testing was the arithmetic weighted mean (based on Faust, 1990). A shift of zero would be expected if there was no memory distortion, and a positive shift of one would indicate a distortion 1 mm forward in the direction of implied motion. We also used quadratic regressions to estimate shifts for group data (based on Freyd & Finke, 1985). Both methods produced comparable shift estimates in all three experiments, and in instances in which they differed somewhat

Table 1
Percentage of Same Responses for Each of the Three Paths and for Each of the Five Test Positions Used in Experiment 1

	Test position				
Path	−2 mm	−1 mm	0 mm	+1 mm	+2 mm
Straight	35	60	77	60	32
Curved	26	57	75	62	29
Spiral	24	50	69	63	35

in magnitude (the weighted mean tends to be conservatively near zero), the same ordering by condition was always obtained. Collapsed across all conditions, the weighted-mean estimate of shift for this experiment was .038 mm. This shift was not significantly different from no shift at all ($F < 1$, $MS_e = 0.59$).

An analysis of variance (ANOVA) was performed with four variables. Rotation direction of the spiral tube (whether clockwise or counterclockwise) and block order (six orderings were counterbalanced) were between-subjects variables, and path (straight, curved, or spiral) and exit direction of the ball (upward, downward, leftward, or rightward) were within-subjects variables. The ANOVA revealed only two significant main effects and no significant interactions. Exit direction produced a significant main effect, $F(3, 36) = 9.81, p < .001$, $MS_e = 0.16$. This main effect was due to the difference in shifts for upward–downward directions from rightward–leftward directions (upward, −.163 mm; downward, .017 mm; rightward, .122 mm; leftward, .178 mm). This horizontal–vertical asymmetry has been previously obtained (Hubbard & Bharucha, 1988), such that shifts are greater for leftward–rightward directions than for upward–downward directions. This effect of exit direction was not of theoretical interest to us in the current study, and it did not interact with path ($F < 1$), so we did not consider it further.

Of most interest to us was the main effect for path, $F(2, 24) = 5.16$, $p = .014$, $MS_e = 0.13$ (see Table 1). We had predicted that we would find a main effect of path because of the superiority of straight paths over spiral paths. However, the path effect we found was due to exactly the opposite ordering of shift magnitudes than we had predicted. The shifts for the straight, curved, and spiral paths were, respectively, −.044, .035, and .124 mm. In other words, the spiral path produced the largest shift. These surprising results are displayed in the bottom half of Figure 2; they contrast sharply with our prediction (cf. Figure 2, top half). The straight and curved path shifts were not significantly different from zero: ($|t| < 1$ in both cases). The forward shift for the spiral path, consistent with a representational momentum effect, was marginally and significantly different from zero, $t(23) = 1.80, p = .08$ (two-tailed), $SE = .07$. These differences in shift reflect differences in the asymmetry of the distribution of same responses around the to-be-remembered position, not differences in overall probability of responding same or different; in each path condition, the percentage of same responses averaged across test positions was 52.

The ordering of memory shifts for the three paths in the representational momentum task was, from lowest to greatest, straight, curved, and spiral. We wondered whether our questionnaire data would shed light on this surprising result. We found, however, that 63% of the subjects selected the straight path as the ball's expected trajectory on the pencil-and-paper task; 33% selected the curved path; and only 4% selected the spiral path. Thus, the results on the classic spiral tube problem were in direct contrast to the results for the representational momentum task. Furthermore, we could find no evidence of individual differences such as a relationship between performance on one task with the other. We also found no evidence of a relationship between either physics background or gender with performance on either the pencil-and-paper task or the representational momentum results for path types. The surprising results from Experiment 1 demanded replication.

Experiment 2

Contrary to our predictions, the shifts for the straight path in Experiment 1 were smaller than those for the curved path, which were in turn smaller than those for the spiral path. This

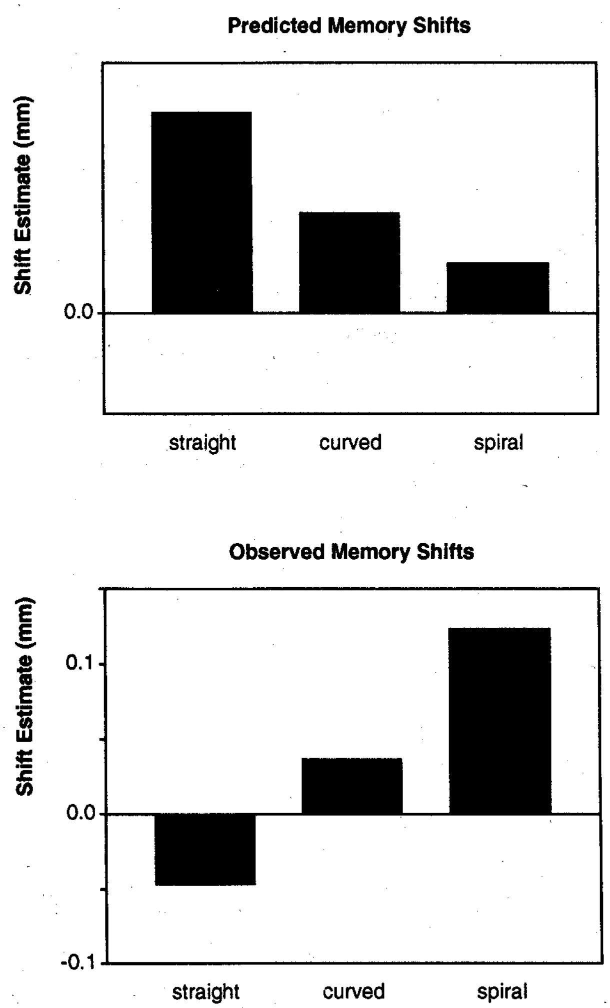

Figure 2. Predicted and observed memory shift estimates (arithmetic weighted means) for Experiment 1.

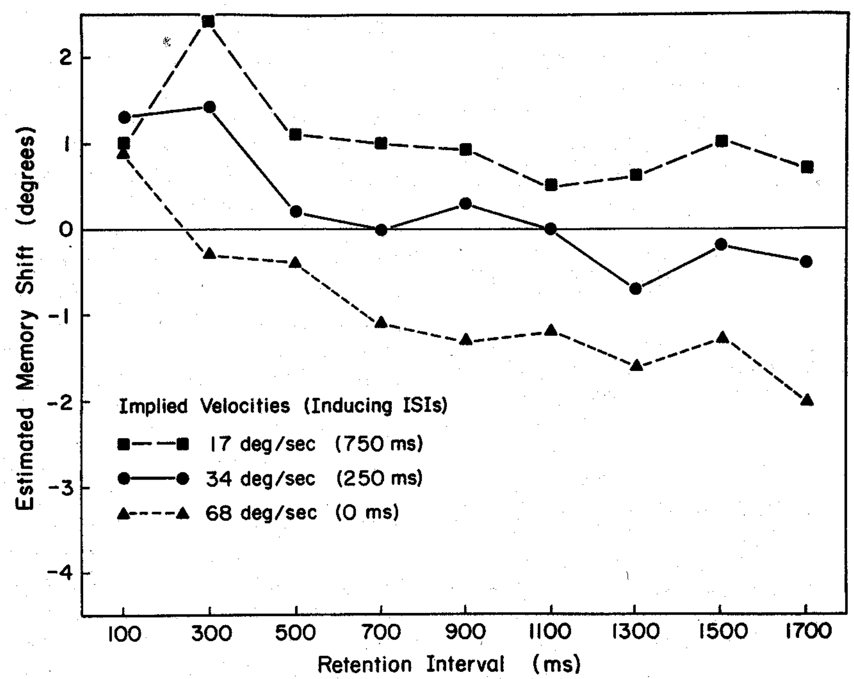

Figure 3. Shift estimates (based on quadratic regressions) plotted by retention interval for each of the three implied velocities of the inducing display used in Experiment 3 (Freyd & Johnson, 1987). ISI = interstimulus interval. From "Probing the Time Course of Representational Momentum" by J. J. Freyd and J. Q. Johnson, 1987, *Journal of Experimental Psychology: Learning, Memory, and Cognition, 13,* p. 264. Copyright 1987 by the American Psychological Association.

ordering suggests that the spiral path is the perceptually "natural" path for continuation of spiral motion.

In the remaining two experiments, we replicated the basic conditions of Experiment 1 while manipulating retention interval. Retention interval is expected to produce an effect on the overall shifts, such that with long retention intervals the shifts become negative (Freyd & Johnson, 1987; Freyd, Kelly, & DeKay, 1990). In these previous studies in which retention interval was varied, it was found that memory shift increased with retention interval for very short retention intervals and then decreased for longer intervals, producing an upside-down U-shaped curve. This curve was modeled as a result of two different mechanisms, a fast-rising representational momentum effect that causes memory shift to grow with retention interval because of a continuous memory transformation, and a slower acting memory "averaging" effect that causes memory shift to decrease with retention interval as the central tendency of the preceding display assumes ever-increasing prominence in memory over the most recent positions viewed. This two-mechanism model was supported by the experimental data in Freyd and Johnson (1987). Furthermore, it was found that the peak of the retention interval function appeared to vary with velocity, such that the curve peaked earlier (before 200 ms) for faster velocities and later (after 200 ms) for slower velocities in the range of velocities examined (Freyd & Johnson, 1987).

Figure 3 displays the results from Freyd and Johnson's (1987) Experiment 3 in which retention interval was varied between 100 and 1,700 ms. We compared three inducing velocities. It is difficult to directly compare the velocities used in Freyd and Johnson's experiments (in which the inducing display was a rectangle rotating about its axis, and thus velocity was expressed as degrees of rotation per second) with the current displays involving a ball moving through a spiral tube. The velocity of the ball in the spiral tube was approximately 113 mm per second of linear distance through the spiral. However, we can directly compare stimulus onset asynchronies (SOAs). In the Freyd and Johnson displays, there was a 250-ms stimulus duration for each presentation of the rectangle in the inducing display. Interstimulus intervals (ISIs) were varied from 0 to 750 ms, and thus SOAs varied from 250 ms to 1,000 ms. In the spiral display there was a 150-ms SOA (0-ms ISI and 150-ms stimulus duration), which is shorter than the shortest SOA used by Freyd and Johnson. Because the 17-mm linear distance the ball traveled for that 150-ms SOA is comparable to the distance traveled by the end points of the rectangle in the Freyd and Johnson displays, we assumed that the velocity in the current experiments was comparable to the fastest velocity Freyd and Johnson used. We thus predicted that longer retention intervals would produce a decrease in memory shift for our spiral display. In Experiment 2, we used a retention interval of 250 ms instead of the 150-ms interval used in Experiment 1.

Method

Twenty-four additional subjects recruited from the University of Oregon community were paid for their participation in this experi-

Table 2
Percentage of Same Responses for Each of the Three Paths and for Each of the Five Test Positions Used in Experiment 2

Path	Test position				
	−2 mm	−1 mm	0 mm	+1 mm	+2 mm
Straight	42	66	81	56	30
Curved	31	64	78	64	37
Spiral	26	58	75	65	37

ment. The methods used in Experiment 2 were identical to those used in Experiment 1, except that the first display was followed by a 250-ms retention interval instead of a 150-ms retention interval.

Results and Discussion

The percentages of same responses for each condition and each subject were again calculated. Collapsed across all conditions, the estimate of shift for this experiment was .011 mm. This shift was not significantly different from no shift at all ($F < 1, MS_e = 0.34$).

As with Experiment 1, we performed an ANOVA with four variables. Rotation direction of the spiral tube (whether clockwise or counterclockwise) and block order (six orderings were counterbalanced) were between-subjects variables, and path (straight, curved, or spiral) and exit direction of the ball (upward, downward, leftward, or rightward) were within-subjects variables. The ANOVA revealed three significant main effects and one interaction. As in Experiment 1, exit direction produced a significant main effect, $F(3, 36) = 9.41$, $p < .001$, $MS_e = 0.14$. Again, this main effect is due to the difference in shifts for upward–downward directions from rightward–leftward directions. Unlike Experiment 1, there was a main effect of rotation direction, $F(1, 12) = 7.12, p < .05$, $MS_e = 0.34$, and an interaction between rotation direction and exit direction, $F(3, 36) = 5.10$, $p < .01$, $MS_e = 0.14$. The rotation direction effect was due to a higher shift for clockwise than counterclockwise motion. The effects of exit direction and rotation were not of theoretical interest to us, and neither interacted with path (Fs < 1), so we did not consider them further.

Of most interest to us was the main effect for path, $F(2, 24) = 16.46$; $p < .001$, $MS_e = 0.10$ (see Table 2). This main effect reflected exactly the same ordering of paths as found in Experiment 1. The shifts for the straight, curved, and spiral paths were, respectively, −.135, .041, and .127 mm. In other words, the spiral path produced the largest positive shift. The straight path shift, $t(23) = -2.77, p < .05, SE = .05$, was significantly different from zero. The curved path shift ($|t| < 1$) was not significantly different from zero. The forward shift for the spiral path, consistent with a representational momentum effect, was significantly different from zero, $t(23) = 3.08, p < .01, SE = .41$.

The questionnaire data were identical to that found for Experiment 1: Of the subjects in this experiment, 63% selected the straight path as the ball's expected trajectory on the pencil-and-paper task, 33% selected the curved path, and only 4% selected the spiral path. Once again we found no evidence of individual differences, such as a relationship between performance on one task with performance on the other, nor of a relationship between either physics background or gender with performance on either the pencil-and-paper task or the representational momentum results for path types.

Experiment 2 served to replicate the main results from Experiment 1. The same ordering of the three paths was obtained in the representational momentum task so that from least positive to most positive the order was straight, curved, and then spiral. There was not much evidence that changing the retention interval had a large consistent effect on the shifts. The questionnaire data from both Experiments 1 and 2 indicated that when subjects were asked to select what they believed to be the correct trajectory from a set of three paths, a majority of them chose the physically correct straight path.

Experiment 3

Experiment 3 was designed to replicate once more the surprising ordering of memory shifts for the three exit paths of the spiral tube in the momentum task. In addition, we used a longer retention interval to confirm that the parametric relationship between memory shift and retention interval was like that in previous studies (Freyd & Johnson, 1987).

Method

Twenty-four additional subjects recruited from the University of Oregon community participated in this experiment. Nine of the subjects received course credit, and the remaining 15 subjects were paid for their participation. The methods used in Experiment 3 were identical to those used in Experiment 1 except that the first display was followed by a 500-ms retention interval instead of a 150-ms (Experiment 1) or a 250-ms (Experiment 2) retention interval.

Results and Discussion

As in Experiments 1 and 2, we calculated the percentages of same responses for each condition and for each subject. Collapsed across all conditions, the estimate of shift for this experiment was −.15 mm. This shift was significantly different from zero, $F(1, 12) = 13.72, p < .01, MS_e = 0.44$.

As with Experiments 1 and 2, we performed an ANOVA with four variables. Rotation direction of the spiral tube (whether clockwise or counterclockwise) and block order (six orderings were counterbalanced) were between-subjects variables, and path (straight, curved, or spiral) and exit direction of the ball (upward, downward, leftward, or rightward) were within-subjects variables. The ANOVA revealed two significant main effects and one interaction. As in Experiment 1, exit direction produced a significant main effect, $F(3, 36) = 22.90$, $p < .001$, $MS_e = 0.13$. Again, this main effect was due to the difference in shifts for upward–downward directions from leftward–rightward directions. Like Experiment 1, but in contrast to Experiment 2, there was no main effect for rotation direction ($F < 1$) nor an interaction between rotation direction and exit direction, $F(3, 36) = 1.68, p > .15, MS_e = 0.13$. Experiment 3, however, produced a marginally significant new interaction between path and rotation direction, $F(2, 24) = 3.43$, $p = .05$, $MS_e = 0.09$. Because rotation direction was a between-subjects variable, and this small interaction was not representational momentum task before completing the pencil-and-paper task.

General Discussion

In direct contrast to our initial predictions, Experiment 1 revealed that the representational momentum memory shift for a ball following a spiral path after exiting a tube is greater than the memory shift for a ball following the physically correct linear path. A curvilinear path, midway between the spiral and straight paths, produces shifts midway between those for the other two paths. Experiments 2 and 3 replicated this ordering of the three paths. The three experiments taken together also replicate retention interval results previously reported for representational momentum (Freyd & Johnson, 1987; Freyd et al., 1990). The results of pencil-and-paper questionnaires given to subjects after completing the memory task indicated that our subjects had relatively accurate conscious knowledge of the trajectory of a ball exiting a spiral tube (63% to 83% chose the correct path; only 4% chose the spiral path).

Although our initial predictions were resoundingly falsified, the results reported here are, in many respects, consistent with previously reported effects for representational momentum. For instance, Hubbard and Bharucha (1988) and Verfaillie and d'Ydewalle (1991) have reported that the momentum occurs along a path that is consistent with the inducing display. In our experiments, simple pattern completion or good continuation would place the momentum along the spiral path. Alternatively, perceptual assumptions of animacy would also account for the superiority of the spiral path (Freyd, 1992; Freyd & Miller, 1992). If humans are especially evolved to process animate motion (Shiffrar & Freyd, 1990, 1993), subjects may attribute (at the perceptual level) internal force to the moving ball as is the case with animate objects. This internal force would permit the ball to continue to move in a spiral path even after leaving the tube.

The results are also consistent with a claim of relative cognitive impenetrability (Finke & Freyd, 1989; Kelly & Freyd, 1987) in that subjects showed a memory shift for a path that the majority of subjects did not consciously consider correct. Furthermore, our instructions to subjects about how to interpret the spiral tube display emphasized the physical constraints, such that the accurate path could be consciously understood to be the straight line trajectory. The fact that these verbal instructions did not seem to influence the memory shifts is in keeping with Finke and Freyd's (1985) finding that feedback and practice do not mitigate the memory shifts either. In other words, it appears that representational momentum operates with relative cognitive impenetrability.

Our results indicate a departure from the notion that representational momentum is simply an internalization of physical momentum. This departure is in line with an interpretation of representational momentum that Freyd has been encouraging for some time (Freyd, 1987, 1992, 1993). In Freyd's interpretation, representational momentum is understood to be a necessary characteristic of a representational system with spatiotemporal coherence, just as physical momentum is a property of objects embedded in a spatiotemporal world. However, this property is not otherwise directly linked to the internalization of naive physics. Instead, Freyd predicts representational momentum effects for any dimension affording continuous transformation independent of the physical plausibility.

Carey (1986) wrote: "We cannot effect scientific understanding without grasping the depth and tenacity of the student's preexisting knowledge" (p. 1127). Perhaps some of the "tenacity" of this preexisting knowledge comes from properties of the perceptual–representational system. Perhaps, in particular, people create dynamic mental images when attempting to reason about physical laws, and various properties of those dynamic images influence the outcome of the reasoning process. The erroneous belief that objects continue to travel in a curved path even after external force is removed (see McCloskey, 1983) might have a partial basis in the inertial properties of dynamic representations. In particular, representational momentum along a chosen path may solidify the dominance of that path. According to this account, it is not the selection of a path per se for which representational momentum is responsible (see Finke & Freyd, 1989) but the solidification of that path in the reasoning process because of inertial properties. Alternatively, in some naive physics situations the representational momentum effect itself may influence path selection. If, for instance, in our displays the path determined by the spiral tube causes representational momentum along that path even as the tube ends, such momentum might bias subjects to continue to extrapolate along a spiral path. Perhaps when reasoning about the situation, some subjects prefer a curved path because they unknowingly combine the spiral path (solidified by inertial properties) with the straight path (the physically correct path) and arrive at the curved path. If our speculation is correct that inertial properties of dynamic representations are behind some naive physics errors, educators teaching principles of Newtonian mechanics might find it valuable to work directly with the perceptual system through animated displays designed to compensate for these biasing properties of the representational system.

In future studies it would be valuable to explore further the role of ecological validity in representational momentum, naive physics research, and physics education. By some measures, our display is "impoverished" relative to, say, a real spiral tube with a real metal ball. Yet, in comparison with most illustrations in mechanics text books, or in comparison with the majority of experimental displays used in research and perception, our display is relatively rich. (Ironically, in attempts to investigate erroneous beliefs about physical systems, impoverished stimuli may have a certain ecological validity.) Nonetheless, it is important to assess the role of stimulus impoverishment in future experiments. For instance, if our display were a full-color and high-resolution video of a real spiral tube, would our results on the memory task replicate? We predict such a display would, at the least, increase the magnitude of the representational momentum shifts themselves (which would be valuable in any case), but would the relative shift magnitudes for the three paths differ if a rich display were used?

Similarly, if our computer display were oriented horizontally instead of vertically, would that make a substantial change, perhaps because of an implicit representation of gravity given a vertical orientation? (An analysis of the results for our different path conditions for different exit directions and rotation directions revealed no evidence that gravity effects could explain our findings, but a direct test is still in order.) In future studies, we would also recommend using an even larger set of exit directions than the four used in the current studies. All of our straight path conditions involved an exit path along a canonical orientation (horizontal or vertical); what would happen if the straight path was oblique relative to the screen coordinates? (We did run a pilot experiment with 12 subjects, presenting exit directions rotated 45 ° from the screen dimensions, and found that the shifts of the curved and spiral paths were positive and the straight path negative, but the experiment did not achieve statistical significance. It did suggest, however, that the canonical orientations are not responsible for the small straight path shifts.)

In summary, the three experiments reported here indicate that the perceptual representation formed when viewing a ball moving through a spiral tube leads to anticipation of motion along the spiral path even after the ball exits the tube. This perceptual representation operates despite conscious beliefs to the contrary, and indeed it is perhaps because of such automatic dynamic anticipations that humans are sometimes inaccurate in naive physics tasks. Future research may shed more light on the relationship between these perceptual anticipations and conscious beliefs, producing suggestions for educational intervention.

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