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Probing the Time Course of Representational Momentum

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Observers saw a rectangle at three orientations along a path of rotation. They attempted to remember the third orientation and were then tested with a fourth orientation that was either the same as, or slightly different from, the third. As in previous *representational momentum* studies we find that memory for position is distorted in the direction of the implied motion, in analogy to physical momentum. We now report that memory shift increases with retention interval for small intervals, as predicted by the analogy. However, instead of reaching some asymptotic value, the memory shift then decreases with retention interval. The resulting U-shaped curve may be considered the result of two competing effects: a positive memory shift attributable to representational momentum, which dominates at short intervals, and a negative shift attributable to memory averaging effects, which dominates at longer intervals. The memory averaging effect increases with retention interval and is strongest for faster presentation rates. For very short retention intervals the rate of increase in memory shift is proportional to the implied velocity of the inducing display, as predicted from the analogy to physical momentum.

Under appropriate conditions an observer's memory for the final position of an abruptly halted object is distorted in the direction of the represented motion, much as a physical object continues along its path of motion because of inertia. Freyd and Finke (1984) introduced the term *representational momentum* to refer to this phenomenon. They proposed that representational momentum stems directly from the importance of detecting and representing movement for human perception and cognition; memory for an object's position is apparently intimately tied to knowledge of that object's previous motion. Furthermore, the finding suggested that mental mechanisms responsible for representing motion may exhibit properties analogous to properties of physical motion such as inertia. In the present study we began by exploring one prediction made by the analogy to physical momentum: that representational momentum should increase with retention interval until some asymptotic memory distortion is reached.

Previous Studies

Freyd, Finke, and their collaborators (Finke & Freyd, 1985; Finke, Freyd, & Shyi, 1986; Finke & Shyi, 1987; Freyd & Finke, 1984; Freyd & Finke, 1985; Kelly & Freyd, in press) have found representational momentum effects under a variety of experimental conditions. In their original study Freyd and Finke (1984) presented subjects with three orientations of a rectangle sampled from a path of rotation about the rectangle's center and instructed them to remember the third position.[1] The subjects' memories were then tested by asking them to decide if a fourth rectangle, presented at the same orientation as the third, or rotated slightly forward or backward, was in fact at the same orientation. Subjects were much less likely to reject forward displacements of the rectangle than backward displacements, presumably because their memory of the third position was distorted in the direction of the implied motion. Similarly when subjects correctly rejected distractors, they took longer to do so for forward distractors than for backward distractors.

In this study, we used a more sensitive technique for investigating the memory distortion that was introduced by Freyd and Finke (1985). As in the first study, subjects were shown an ordered sequence of three orientations of a rectangle depicting rotation around its central axis and asked to make a same/different judgment when shown a fourth, "test", orientation of the rectangle. However, the new procedure used a different distribution of test orientations: nine different test orientations were presented equally often and only one of those orientations was truly the same. Four of these nine test orientations were clockwise rotations from the third orientation and four were

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[1] A sequence of static displays, rather than continuously moving displays, were used by Freyd and Finke (1984) for two reasons. First, the representational momentum study followed work by Freyd (1983) that investigated the perception of dynamic information in static pictures. Second, Freyd and Finke wanted to avoid residual aftereffects of motion (e.g., Mayhew & Anstis, 1972). Such aftereffects would be in the direction opposite that of any actual motion of the inducing display; hence, they might serve to suppress a momentum effect.

counterclockwise rotations. Every subject Freyd and Finke (1985) tested produced 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.

There is also evidence that the magnitude of that memory shift is a linear function of the implicit velocity of the inducing display (Freyd & Finke, 1985). This was predicted from the momentum metaphor, as physical momentum is proportional to velocity. Quadratic regression curves were fit to the data for each of several implied velocities, and the peaks of the curves were then evaluated. The peaks are considered to be estimates of the amount of memory shift. Freyd and Finke (1985) reported a correlation of .9 for degree of memory shift and the implied velocity of the inducing display.

The finding of a velocity effect was extended by Finke et al. (1986) in two ways. First, they found a velocity effect for the independent linear displacements of dots on a computer screen instead of for a rigidly rotating rectangle. Second, by using implicit accelerations they showed that observers are sensitive to the implied final velocity and not merely the average velocity. Implied velocities and accelerations were manipulated by varying the distance between dots in successive displays while holding temporal parameters constant.

In an earlier study, Finke and Freyd (1985) had reported finding a representational momentum effect for the linear, independent, displacements of dots, even when interstimulus intervals (ISIs) for either inducing stimuli or retention periods were 2 s. Finke and Freyd argued that this finding ruled out sensory mechanisms for the effect. In their study, however, the more sensitive measure of degree of shift introduced in Freyd and Finke (1985) was not used; instead, the magnitude of the effect was measured in terms of the difference between responses to a single forward and single backward distractor position. Thus, although representational momentum may not depend on sensory mechanisms, the question remained open as to whether there are systematic effects dependent on inducing display rates or retention intervals. Indeed, the findings reported by Freyd and Finke (1985) and Finke et al. (1986) suggest that inducing display rates do matter. In the present paper we investigate the possibility that the degree of memory shift is also a function of the retention interval.

The Predicted Relation Between Memory Shift and Retention Interval

The studies discussed so far assumed that the mental representation of the display object's position was fixed in memory at some point forward of the true position. In other words, the assumption was that representational momentum had already had its effect on memory by the time the test display appeared. It thus made sense to equate memory shift (an estimate of the object's position in memory) directly with representational momentum. In the present study we attempt to *probe* the mental representation while representational momentum is having its effect. That is, we investigate the time course of the process. We assume that the memory shift must build up over some time period; thus, we assume that memory shift is a function of representational momentum and the retention interval, or the time that has elapsed between the presentation of the final object in the inducing display and the test display.

To predict the functional relation between memory shift and retention interval, we looked more closely at the physical process of stopping. Consider a coasting automobile as the brakes are applied, or a canoe after the occupants stop paddling. The vehicle will not stop instantly, but will gradually slow from its initial velocity to a stop. Depending on the precise physical situation, the rate of deceleration might take any of several functional forms. For example, ignoring waves and turbulence the canoe will be slowed by hydrodynamic drag proportional to its velocity, $F_f(t) = -kv$. This implies that an ideal canoe will asymptotically approach a final position, p, which depends only on the mass of the boat, m, a drag coefficient, k, and the initial velocity, v_o. At any time, t, the position of the canoe will be directly proportional to the initial velocity:

$$p(t) = (mv_o/k)(1 - e^{-kt/m}). \tag{1}$$

In the limit,

$$p(\infty) = mv_o/k. \tag{2}$$

Alternative models for stopping also exist. For example, a car braking on a smooth surface applies a constant deceleration force ($F = -k$), implying a final stopping distance proportional to the square of the initial velocity; $p(t) = v_ot - kt^2/2m$, so $p(\text{final}) = mv_o^2/2k$. Similarly, a canoe in turbulence might be better modeled as decelerating with a force proportional to the velocity squared; $F = -kv^2$. (Our preferred model is accurate only for very slowly moving objects in a fluid.) This would imply a position that increases with the log of time: $p(t) = (m/k)\ln(1 + kv_ot/m)$. We considered these models less plausible because they did not correspond to the linear relation between initial velocity and position reported in Freyd and Finke (1985).

Applying our preferred physical model (Equation 1) to the representational momentum task, we equated p to memory shift, t to retention interval, and v to the internal rate of transformation. We predicted that the degree of memory shift should be a function of retention interval but that the function should approach some asymptotic memory shift, as depicted in Figure 1.

Any reasonable physical model predicts that, for short retention intervals, the function relating shift to retention interval can be approximated by a straight line with slope equal to the initial velocity. We assume that v_o, the initial internal rate of transformation, is proportional to the implicit velocity of the inducing display. We therefore predict that the slope of this line should be proportional to the implied velocity of the inducing display. Our preferred model also predicts that the asymptote reached for long retention intervals should be proportional to the implied velocity, as depicted in Figure 1.

Experiment 1

In Experiment 1 we tested the predicted relation between degrees of memory shift and retention interval by holding constant the implied velocity of the inducing display while varying the retention intervals between 10 and 90 ms. We expected to find small or nonexistent memory shifts for the shortest retention intervals and larger memory shifts for the longer retention intervals.

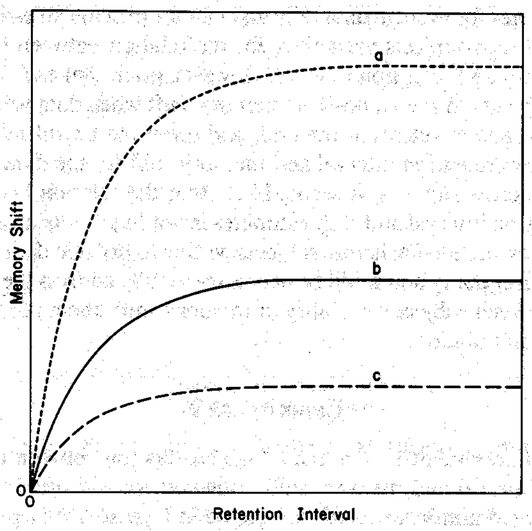

Figure 1. Predicted relations between memory shift and retention interval using a simple physical analogy for representational momentum. (Curve *a* is meant to represent the relationship for a fast inducing velocity, Curve *b* for one half as fast, and Curve *c* for an inducing velocity one fourth as fast.)

Method

Subjects. Subjects were 20 members of the Cornell community who were paid for their participation in this study.

Apparatus and stimuli. Stimuli were presented on a computer-controlled vector-plotting display screen. Each trial consisted of the presentation of a fixation point centered on the screen, followed by the successive presentation of four orientations of a rectangle. The rectangle was always centered on the screen; different orientations were created by presenting the rectangle at some rotated position. The angular disparity between the first and second rectangle, and between the second and third rectangle, was 17°. The fourth rectangle was presented in one of nine equally likely positions: −8°, −6°, −4°, −2°, 0°, 2°, 4°, 6°, or 8° of rotation from the third.

The first three rectangles were always presented with a 250-ms stimulus duration. The test rectangle remained on the screen until the subject had responded. The interstimulus intervals between the first and second and between the second and third rectangles were always 250 ms. The implied velocity of the inducing display was thus 34°/s. (These values were chosen to be consistent with the temporal parameters used in the original Freyd and Finke, 1984, study.)

Nine retention intervals were used, from 10 to 90 ms in steps of 10 ms. Figure 2 shows an example display sequence for an implicit counterclockwise rotation. The three stimulus orientations plus the test pattern, which were presented sequentially in the experiment, are shown from left to right. The test pattern shown on the far right is for a 0° displacement, which matched that of the third pattern in the sequence.

Procedure. Each subject completed two blocks of 243 trials, the first block being practice and the second providing data. The 243 trials, composed of three trials of each of 81 trial types (9 retention-intervals × 9 distractor positions), were randomly ordered for each subject and each block. For 10 of the subjects the inducing display implied a clockwise rotation, and for the other 10 subjects, a counterclockwise rotation. The third position (the to-be-remembered position) of the rectangle was the same for both clockwise and counterclockwise rotations. In fact, the third position was unvaried on all trials of the experiment and for all subjects. The first and second positions were thus identical on all trials for the subjects observing implied clockwise rotations, and a different first and second position were unvaried on all trials for the subjects observing implied counterclockwise rotations.

Subjects were tested individually in a session that lasted about 50 min. Each sat in a well-lighted laboratory room at a comfortable viewing distance from the screen, with his or her dominant foot resting on a pedal and with a single-button response box held in each hand. They initiated each trial by pressing the foot pedal and concluded each trial by pressing one of two response buttons ("same" or "different"). Before they were shown the display, they were asked to read an instruction sheet that emphasized the equal probabilities of a "different" orientation rotated clockwise and one rotated counterclockwise from the third position. However, they were not informed about the frequency of "same" and "different" orientations. Subjects were instructed to respond "same" only when the test orientation was exactly the same as the third position.

Results and Discussion

Figure 3 displays the results averaged across subjects and retention-interval conditions. The memory shift can be estimated

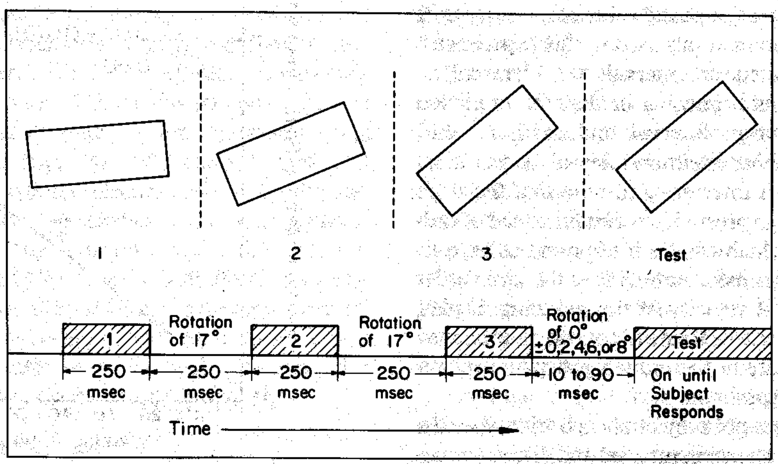

Figure 2. Schematic illustration of a display sequence for an implicit counterclockwise rotation used in Experiment 1.

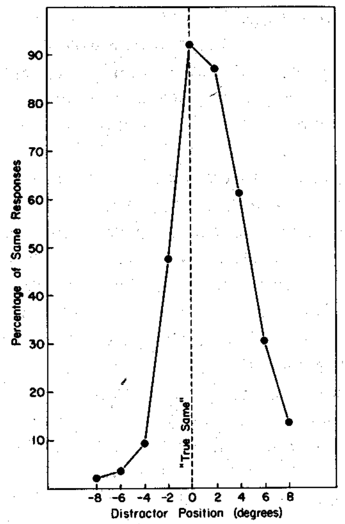

Figure 3. Experiment 1 results averaged across all subjects and retention-interval conditions. (Distractor positions with positive values represent "forward" displacements of the fourth rectangle and negative values, "backward" displacements.)

by subjecting the data to a quadratic regression and solving for the apex or peak of the curve. For these average data the estimated shift is 1.03°. The estimated shifts, averaging across retention interval, for individual subjects ranged between .4° and 2.0°; that is, every subject showed a *positive shift,* a memory shift in the direction of the implied motion. As expected, there was no significant difference ($F < 1$) between the results for the 10 subjects who observed clockwise inducing displays and those who observed counterclockwise inducing displays. For all subsequent analyses direction of rotation will be ignored.

Curves were also fit to the data for each retention-interval condition through quadratic regression, and peaks of the curves were evaluated. As discussed earlier, we predicted that the peak, or estimated memory shift, would increase with the retention intervals until an asymptote was reached. Figure 4 shows a strong increasing linear relationship between retention interval and memory shift ($r = .98$; $p < .0001$).

As Figure 4 also shows, no asymptotic value of memory shift was reached for the retention intervals used in this experiment. We assumed that longer retention intervals would reveal an asymptote. The result seems promising in that the predicted relationship between retention interval and memory shift would be nearly linear for short retention intervals as was illustrated in Figure 1. Also, it is interesting to note that the slope of the regression line, 19°/s (expressed in seconds instead of milliseconds as in Figure 3), which can be interpreted as an estimate of the internal rate of transformation, is of the same order of magnitude as the implied velocity of the inducing display, 34°/s. This suggests that the internal rate of transformation may approximate the external rate of the inducing display, a possibility explored further in Experiment 5.

With only three repetitions per subject of each trial type (the 81 unique combinations of retention interval and distractor position), we did not have enough data to estimate shifts for each retention interval for individual subjects. Thus, we present shift estimates for average data only and cannot provide an estimate of between-subjects variability for the relation between memory shift and retention interval. However, given that each of the 20 subjects showed a positive memory shift when data were averaged across retention interval, and given the lawful relation between retention interval and memory shift for the data averaged across subjects, it seems likely that the relation between retention interval and shift estimates is not highly variable. Future research using heroic subjects willing to provide data gathered over many hours will be necessary to fully address the issue of between subject variability of memory shift under parametric manipulation.

Experiment 2

In Experiment 1 we found a high correlation between retention interval and memory shift. However, we did not find the predicted nonlinear relation depicted in Figure 1. We assumed that this was because our retention intervals were too short. In Experiment 2 we used longer retention intervals, with the hope of discovering the asymptotic value of the memory shift.

Method

Experiment 2 was identical in method to Experiment 1 except that the retention intervals varied between 100 and 900 ms in 100-ms steps (instead of between 10 and 90 ms in 10-ms steps). Another 12 members of the Cornell community were paid for their participation in this study.

Results and Discussion

Data were analyzed as in Experiment 1. Figure 5 shows the memory shifts estimated for each retention interval, as well as those from Experiment 1. As predicted, the memory shift does not increase with retention interval forever; however, instead of reaching an asymptote, the curve appears to peak somewhere between 200 and 300 ms (as judged from the shift estimates for

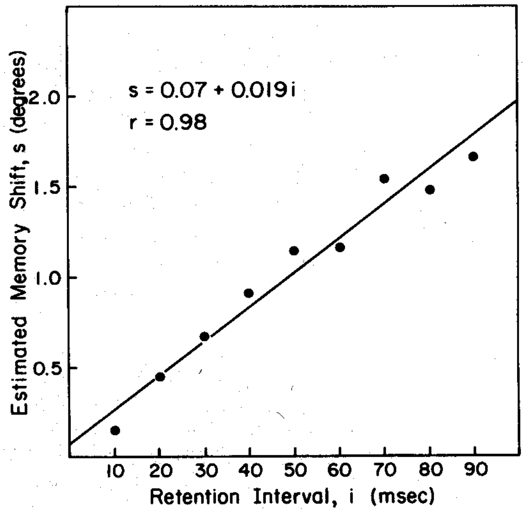

Figure 4. Experiment 1 shift estimates derived from quadratic regressions and plotted against retention-interval condition.

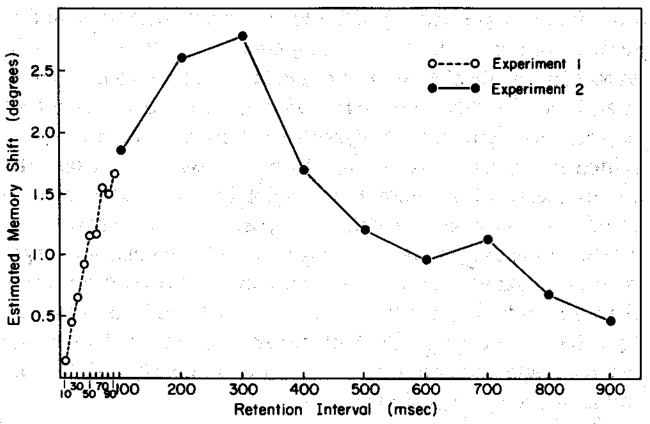

Figure 5. Experiment 1 and 2 shift estimates plotted together.

100-, 200-, 300-, and 400-ms retention intervals) and then to decrease.

Why might the memory shift increase with short retention intervals and then decrease with long retention intervals? We suggest that there are two processes that affect memory distortions: one operating immediately upon perception of the inducing display and the other dominating after some time has elapsed. We assume that the first process is representational momentum. Our best candidate for the latter effect is a memory averaging process in which the static positions of the three rectangles are combined in memory, or, similarly, a process that abstracts the most prototypical position or "central tendency" of the three stimuli (as in Posner & Keele, 1968). If subjects did average static positions in memory or abstract information concerning the central tendency in this way and there was no representational momentum effect, one would expect to see negative shifts. That is, distractors presented in positions closer to the second rectangle should be more confusable with subjects' memory for the third position than distractors presented in forward positions.

We considered the possibility that the shape of the function depicted in Figure 5 might in some way stem from the repeated exposure subjects had of the inducing display positions. The positions of the first three rectangles were the same in every trial, and it is possible that in an attempt to memorize the screen position of the third orientation across trials, certain distortions might have occurred. We therefore tested 12 new subjects in a procedure that differed from Experiment 2 in two ways. First, a slightly different range of retention intervals was used (10, 50, 100, 200, 400, 600, 800, 1000, and 1200 ms), and second, each trial had a randomly selected position for the first rectangle. (Once the position was selected, the remaining positions were determined by the constant angular disparity between rectangle orientations.) We found essentially the same U-shaped relation between memory shift and retention interval, which indicated that the effects at later retention intervals are not dependent on subjects' attempts to memorize the particular location of the third rectangle on the screen across trials.

Experiment 3

Our goals in Experiment 3 were, first, to replicate the surprising U-shaped relation between retention interval and memory shift discovered in Experiment 2, and, second, to see what effect the implied velocity of the inducing display might have on that relation. We therefore used three implied inducing velocities: one that was the same as that used in Experiment 2, one slower, and one faster.

The physical model that we used for our initial prediction (Equation 1) would lead us to predict that at any time, t, the memory shift, p, should be proportional to the internal rate of transformation, v_o, which we assume is proportional to the inducing velocity.

Method

In most respects the methods used in Experiment 3 were the same as those in Experiment 2, except that we altered the range of retention intervals to 100–1700 ms in steps of 200 ms and introduced the additional variable of presentation rate. There were four blocks of trials, one practice and three experimental blocks, differing in the implied velocities of the inducing display. The practice block was shortened to 50 randomly selected trials from the larger set of 243 trials used in Experiment 2. The implied velocity of the inducing display for the practice block was always 34°/s as in Experiments 1 and 2. The implied velocities for the remaining blocks of trials were 17°/s, 34°/s, and 68°/s. Implied velocity was manipulated by varying the ISIs between the first and second, and second and third, rectangle positions (750, 250, and 0 ms, respectively) while holding stimulus durations constant at 250 ms. The order in which blocks were presented was counterbalanced across subjects. Direction of rotation (clockwise or counterclockwise) was also counterbalanced across subjects as it had been in Experiments 1 and 2. Another 12 members of the Cornell community were paid for their participation in this study, which lasted about 80 min.

Results and Discussion

Data were analyzed as in Experiments 1 and 2. Figure 6 shows the estimated memory shifts for each retention interval and each implied inducing velocity. A U-shaped function can be seen for the 17°/s presentation rate; and the results for 34°/s are consistent with a U-shaped function if we assume the curve is peaking somewhere between 100 and 300 ms. (In Figure 5, where the results from Experiment 2 are displayed, the peak for 34°/s seems to be between 200 and 300 ms.) The results for 68°/s are consistent with a U-shaped function if we suppose that the curve peaks before 100 ms. (This assumption is confirmed by Experiment 5.)

For each of the three presentation rates we find that the shift decreases with retention interval for long retention intervals. As Figure 6 shows, we even find negative shifts, where the memory for the third position is distorted in the direction opposite to the implied motion.

Observers report experiencing apparent motion for the 68°/s implied velocity (0-ms ISI), but not for either 34°/s (250-ms ISI) or 17°/s (750-ms ISI). (In earlier pilot work, we found that the ISIs must be reduced to less than 50 ms to achieve a display inducing apparent motion, presumably because of the rather long stimulus durations of the rectangle.)

The main results from Experiment 3 were (a) as in Experiment 2, degree of memory shift was negatively related to retention interval for long retention intervals (there were even negative shifts) and (b) the shift appeared to fall off more quickly with retention interval for fast velocities. Our next step was to

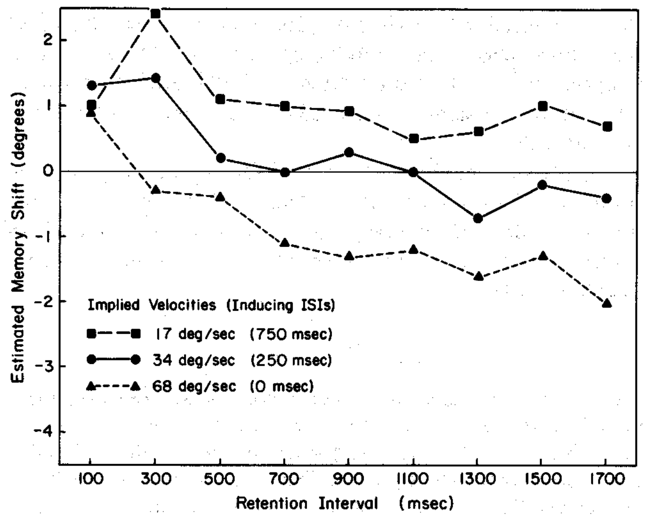

Figure 6. Experiment 3 shift estimates for each of the three implied velocities of the inducing display.

try to show that both of these findings are due to processes separate from representational momentum.

Experiment 4

In Experiment 4 we used a display that was intended to induce no representational momentum, but that was otherwise similar to the display used in Experiment 3. In this way we hoped to show that the memory shift effects for long retention intervals are not dependent on the implied motion that induces representational momentum. The display we used was based on the control experiment used in Freyd and Finke's (1984) original study. In the control the rectangle positions are presented out of order such that subjects see the second position before the first position. In Experiment 4 we used this order of presentation for position while varying the inducing display rates and the retention intervals as for Experiment 3.

In general we expected to find negative shifts, because we hoped to remove momentum effects by showing the orientations out of order. We also expected that the shift would become increasingly negative with retention interval as memory for the third position faded and memory for the central tendency or average position dominated in recognition. (See Posner & Keele, 1970, and Strange, Keeney, Kessel, & Jenkins, 1970, for more on the possibility that memory for exemplars fades much more quickly than does memory for prototypes.) Similarly, we expected that faster display rates would produce greater negative shifts because the three positions, occurring more closely in time, would be more confusable.

One plausible functional relation that fits these predictions is that the memory shift from averaging processes should be linear in time, at least for moderate retention intervals. (Presumably the shift would eventually approach some asymptote located between the three positions of the inducing stimuli.) Assuming such a relation and assuming that actual memory shifts represent a combination of a momentum effect (as in Equation 1) and this memory averaging effect, we generate a revised prediction. Figure 7 presents hypothesized straight lines (p, q, and r) representing a memory averaging effect, plus shifts we might expect for the display used in Experiment 3 (curves $a + p$, $b + q$, and $c + r$) if these lines were added to the exponential curves depicted in Figure 1. The hypothesized lines (p, q, and r) presented in Figure 7 are derived from the assumption that the negative slope of the memory averaging lines increases with the implied velocity of the inducing display. This follows from the expectations that memory averaging effects increase for longer retention intervals (as memory fades) and for faster displays (as the three inducing positions are more confusable) and that all lines have a 0-degree intercept (no shift is expected when the test rectangle position is presented simultaneously with the last inducing rectangle position).

Method

The method used in Experiment 4 was the same as that used in Experiment 3 except that the orientations of the rectangles were presented in a *2, 1, 3* order; that is, what had been the first orientation in Experiment 3 was the second orientation in Experiment 4, and vice versa. Because of this change, we cannot really talk about implied velocities and will instead refer to the different blocks in terms of presentation rates. As in Experiment 3, the three presentation rates for Experiment 4 were manipulated by varying ISIs (0, 250, or 750 ms) for the inducing stimuli while holding stimulus durations constant at 250 ms.

Results and Discussion

Data analyses were performed by following the same procedures used in Experiment 3. The results are plotted in Figure

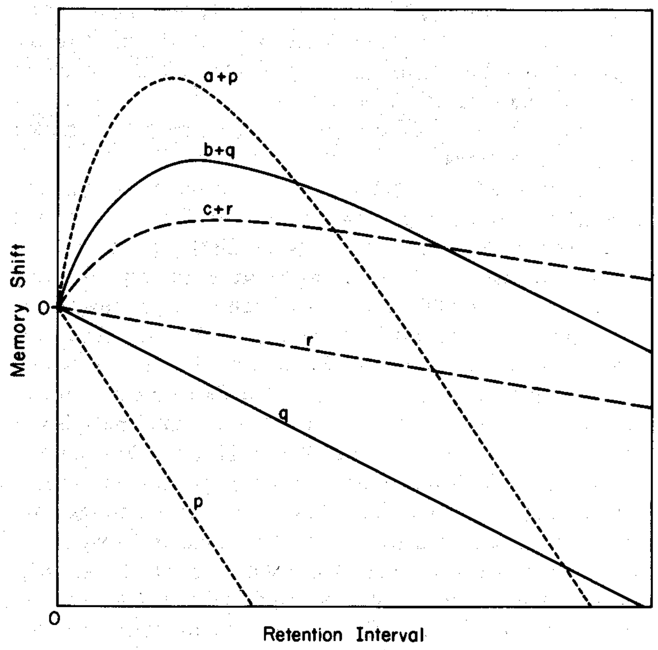

Figure 7. Theoretical functions relating memory shift to retention interval for memory averaging processes alone (lines p for the fastest inducing velocity, q for the middle inducing velocity, and r for the slowest inducing velocity), and for representational momentum (as depicted in Figure 1) combined with memory averaging processes (curves $a + p$, $q + b$, and $c + r$).

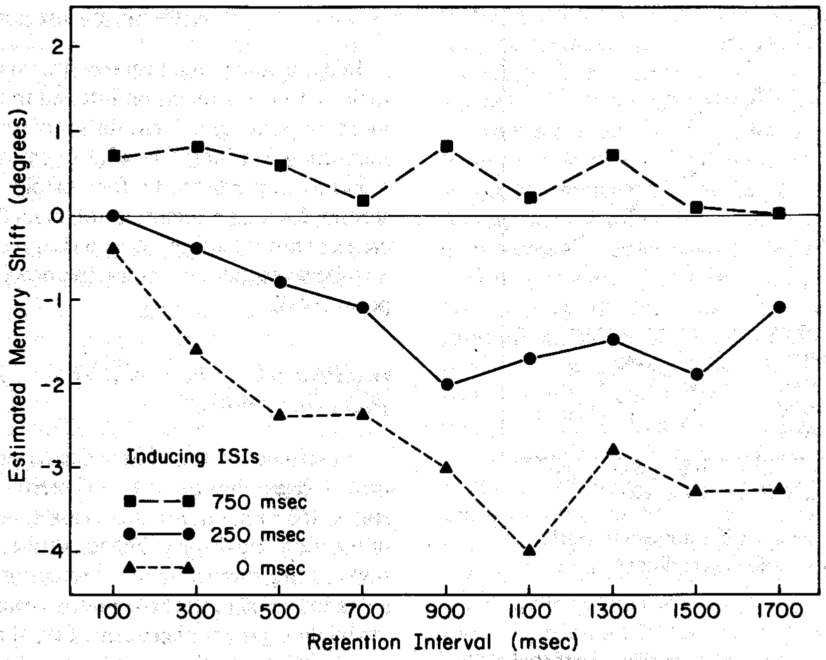

Figure 8. Experiment 4 shift estimates for each of the three presentation rates.

8. The memory shift is clearly influenced by both retention interval and display rate. It differs markedly from the pattern seen in Experiment 3, lending credence to our proposal that there are two different and empirically separable processes at work.

As predicted, the memory shift becomes more negative with increasing retention interval for each ISI condition. Also as predicted, the curves for the three inducing ISI conditions are nonoverlapping, with the shortest ISIs showing the most negative slope. The three curves appear to be approximately straight lines. (Straight lines were predicted for negative shifts relatively near 0°; we would expect the lines to approach an asymptote of −17°, which would correspond to the average of the displayed inducing stimuli.)

Table 1 displays the results of fitting linear regression lines; all three lines are statistically significant. It is also interesting that the estimated slopes (see Table 1) are approximately proportional to the display rates, a possible relation that deserves testing in future studies.

Note, however, that the estimated memory shift is positive in the 750-ms case, counter to our prediction. We believe that this result indicates that Experiment 4 still shows some effect of representational momentum: momentum induced from only the last two stimuli presented. We leave it to future investigations to explore this possibility further; for the present purposes, the results from Experiment 4 are essentially in accord with our predictions.

Table 1
Linear Regression Lines for Each Display Rate Condition When Shift Estimates Are Predicted by Retention Interval

Inducing ISI (in s)	Intercept (in degrees)	Slope (in degrees/s)	*r*	*p*
.750	.84	−.4	.70	.036
.250	−.36	−.9	.71	.033
.000	−1.12	−1.6	.82	.007

Note. ISI = interstimulus interval.

Experiment 5

In Experiment 5 we return to the relation between memory shift and retention interval for very short retention intervals. The results from Experiment 1 suggest that for the shortest retention intervals, the model based on physical momentum is supported in that memory shift increases with retention interval. An additional prediction of the physical model is that the rate of increase, or slope of the function relating shift to retention interval, should be proportional to the implied velocity of the inducing display, and furthermore (assuming that the memory shift is 0 for a 0 retention interval), that the observed memory shift for a particular retention interval should be proportional to the product of that retention interval and the implied velocity.

We also hypothesize, as suggested by the results of Experiment 1, that the internal rate of transformation, v_o, is approximately equal to the inducing velocity; thus, we predict not only that the memory shift attributable to representational momentum should be proportional to the product of the retention interval and implied velocity, but that it should be approximately equal to that product for short retention intervals. As illustrated in Figure 7, we predict that there should be a small offsetting memory shift proportional to retention interval; if, on a first approximation, the memory effect is proportional to inducing velocity, then we predict that the total shift for small intervals

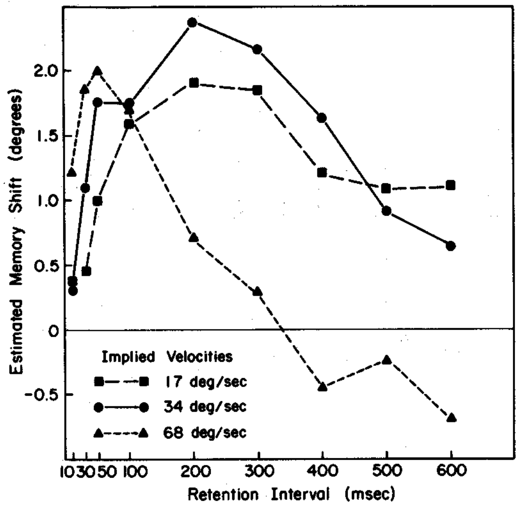

Figure 9. Experiment 5 shift estimates for each of the three implied velocity conditions.

should be linearly related to $v_0 t$, with a coefficient of slightly less than 1.

We tested this prediction by using a range of retention intervals that included some very short times (10 and 30 ms), for three different inducing velocities. As in Experiment 3 our implied velocities were 17°/s, 34°/s, and 68°/s.

Method

The methods used in Experiment 5 were identical to those used in Experiment 3 except that the retention intervals were 10, 30, 50, 100, 200, 300, 400, 500, and 600 ms. Another 12 members of the Cornell community were paid for their participation in Experiment 5.

Results and Discussion

The data were analyzed as for Experiments 3 and 4. Figure 9 displays the shifts by retention interval for each of the three implied velocities. We again found the U-shaped function relating shifts to retention intervals for each implied velocity, corresponding quite well with the predicted curves depicted in Figure 7.

We predicted that for very short retention intervals, the observed memory shift would be proportional to the product of the implied velocity of the inducing display and the retention interval, with a coefficient of slightly less than 1. To test this hypothesis we performed a linear regression by using the observed and predicted memory shifts for the 10- and 30-ms retention interval positions for each of the three implied velocity conditions. The resulting regression equation is shift $= .20 + .84 v_0 t$. The correlation between predicted and observed shift is significant ($r = .91, p < .01$). As expected, the b coefficient (.84) is slightly less than 1. This analysis is fairly crude because we do not have sufficient data to predict the precise functional form of the memory effect. However, the analysis does confirm the predictions of the momentum model and suggests that internal rates of transformation are approximately equal to the external rates implied by the inducing display.

General Discussion

Taken together, the five experiments reported here show two major effects for retention interval in the representational momentum paradigm: First, for short retention intervals the momentum effect increases with retention interval (Experiments 1 and 5) as predicted by the analogy to physical momentum; second, for longer retention intervals the momentum effect decreases with retention interval (Experiments 2 and 3), presumably because memory averaging processes then dominate (Experiment 4).

Implications of the Findings for Short Retention Intervals

Experiments 1 and 5, in which short retention intervals were used, suggest that the rates of internal transformation that result in the momentum effect closely reflect external properties of the inducing display: For Experiment 1 the slope of the function relating memory shift to retention interval (which gives us an estimate of the rate of internal transformation over the 90 ms following the presentation of the third rectangle orientation) was found to be of the same order of magnitude as the implied velocity of the inducing display. Similarly, in Experiment 5 we found that memory shift is approximately equal to the product of retention interval and inducing velocity for short retention intervals. Our tentative conclusion based on Experiments 1 and 5 is that the internal rates of transformation are not only proportional to the external rates of transformation, but are approximately equal to those rates.

An additional implication of Experiments 1 and 5 concerns the nature of the mental representational system used by subjects in these experiments. As in Cooper's (1976) study, in which she probed subjects while they were engaged in mental rotation, our results are consistent with the hypothesis that the mental representation of an object follows a transformational path that has many properties in common with transformational paths in the real world. Just as Cooper's subjects apparently represented objects in numerous intermediate positions along the pathway (they took a constant amount of time to respond to a probe presented at an angular disparity coinciding with the angular disparity predicted for the mentally rotated object at any given time), our subjects apparently represented the rectangle at numerous intermediate positions along a representational pathway (for their estimated shifts increased with time as predicted for short retention intervals). Although some have disagreed, Cooper's finding is often considered strong support for the theoretical position that mental transformations may be analogous to external transformations. One contribution our study might make to this issue stems from the nature of the task we use; unlike subjects in mental rotation experiments, our subjects are strongly discouraged from engaging in any sort of internal transformation because they are asked to remember a static position, yet they still behave in a manner consistent with the hypothesis that mental transformations may be analogous to external transformations. It is hard to see how demand characteristics or subjects' tacit knowledge (Pylyshyn, 1981) could explain our findings. Similarly, to the extent that internal rates of transformation approximate the external rates of transformation, as our experiments suggest, additional support is provided for the hypothesis that mental transformations share processes used during perception (see Shepard & Podgorny, 1978).

Implications of the Findings for Longer Retention Intervals

Previous representational momentum studies may be reconsidered in light of the present results for long retention intervals. Finke and Freyd (1985) reported no decrease in the representational momentum effect for variations in retention interval from .5 to 2 s. Perhaps they failed to find retention interval effects because their method of comparing the strength of the momentum effect was not sufficiently sensitive. In the present study we estimate memory shift by subjecting the percentage of same responses to each of nine distractor positions to quadratic regressions, as introduced by Freyd and Finke (1985). Finke and Freyd (1985), on the other hand, did not estimate memory shifts, but simply compared the differences in responses to a single forward and a single backward distractor position. Alternatively, the different inducing displays might imply quite different parameters for the strengths of momentum and averaging effects.

Freyd and Finke (1985) and Finke et al. (1986) reported velocity effects for representational momentum, such that higher implied velocities lead to greater memory shifts in the direction of the implied motion. The present results make clear, however, that such a velocity effect is only present for relatively short retention intervals; for longer retention intervals the opposite effect obtains (Experiments 3 and 5). We interpret this reversal in the velocity effect as a consequence of memory averaging processes, where faster displays lead to more confusion between the three positions and thus a greater memory shift in the direction opposite to the implied motion. In any case, the present results must be considered as placing restrictions on the generality of the previously reported velocity effect (Freyd & Finke, 1985; Finke et al., 1986).

Applying a Physical Model to Representational Momentum

Despite the limits to applying a model of physical momentum to representational momentum, we believe that under appropriate conditions our preferred physical model predicts the data quite well. In particular, for short retention intervals the predicted relation between memory shift and retention interval, and between memory shift and inducing velocity, holds. As we discussed earlier, the limiting factor when retention interval is varied seems to stem from other cognitive processes, namely, memory processes that abstract the central tendency or average stimulus orientation.

Finke et al. (1986) also reported limits to the physical model for the velocity effect; they found that, for forward accelerations, increases in the final velocity create smaller increases in the amount of memory shift at higher final velocities. This suggests that one could find a maximum velocity beyond which the momentum effect does not increase, presumably because there are limits on the speed of performing mental transformations (see Shepard, 1984). If so, the approximate equality of the internal rate of transformation and the implied rate of the external inducing display, as suggested by the present investigation, would hold only for rates within a certain range.

There are at least two additional parameters of the physical model (see Equation 1) that remain to be investigated for representational momentum: the drag coefficient and the mass of the object, each of which influences the rate at which the object approaches a stopping position. What are the mental analogues to these parameters? One possibility is that mental representations of physical systems include estimates of these physical parameters based on properties of the stimulus display. For instance, it is possible that by using more realistic displays, the memory shift could be increased by displaying an apparently massive object, or by showing a slippery or streamlined object.

Alternatively, the drag coefficient and/or mass may be analogous to more psychologically abstract concepts such as the perceptual salience of the inducing display. For instance, the memory shift may be a function of the number of inducing display positions. Pilot data that we have collected indicates that increasing the number of inducing stimuli from the three used in these experiments to four leads to increased memory shifts; such characteristics of the inducing display might plausibly influence how central motion is to the mental representation, and hence how difficult it is to represent the object as stopped.

Future studies should also attempt to determine more precisely which physical model of stopping is the best predictor for the relation between memory shift and retention interval. As was discussed earlier, we chose one possible model (Equation 1) because it corresponded with the previously reported linear relation between memory shift and inducing velocity. Perhaps, however, one of the alternative, more realistic physical models is more appropriate. The functional form might even depend on the inducing display; perhaps an apparently sliding object would induce a deceleration function appropriate to friction, whereas an apparently floating object would induce a different function. An empirical comparison of the alternative models might be made, given sufficiently sensitive data, by looking at the functions relating memory shift to retention interval for a range of inducing velocities. Before this analysis is performed, however, it will be necessary either to find a display that produces representational momentum without any concomitant memory averaging processes or to have determined more precisely exactly what those memory averaging processes are contributing to estimates of memory shift.

Concluding Remarks

One might ask why we have representational momentum. This issue has been addressed in other articles, most thoroughly in Kelly and Freyd (in press). The favored interpretation has been that representational momentum results from an adaptive internalization of physical momentum. For instance, the tendency to extrapolate an object's motion beyond a final observed position may help us to predict the future position of that object despite our inability to maintain constant eye contact with it. We believe that this interpretation is supported to the extent that the momentum effect can be predicted from the physical model. In the present study we have found additional support for the physical model: Retention interval influences shift estimates as predicted, assuming that separate memory averaging processes operate in conjunction with representational momentum. What is perhaps most significant is that we have found that internal rates of transformation reflect the external rates of stimulus presentation.

Whether or not one sees representational momentum as an adaptive internalization of physical momentum, the phenomenon is apparently lawful and conducive to precise measurement and investigation. Finally, given the ease and reliability with which we and others have observed this effect, it seems likely that representational momentum is basic to representations of objects and events.

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