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Transformations of Visual Memory Induced by Implied Motions of Pattern Elements

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Four experiments measured distortions in short-term visual memory induced by displays depicting independent translations of the elements of a pattern. In each experiment, observers saw a sequence of 4 dot patterns and were instructed to remember the third pattern and to compare it with the fourth. The first three patterns depicted translations of the dots in consistent, but separate directions. Error rates and reaction times for rejecting the fourth pattern as different from the third were substantially higher when the dots in that pattern were displaced slightly *forward,* in the same directions as the implied motions, compared with when the dots were displaced in the opposite, *backward* directions. These effects showed little variation across interstimulus intervals ranging from 250 to 2,000 ms, and did not depend on whether the displays gave rise to visual apparent motion. However, they were eliminated when the dots in the fourth pattern were displaced by larger amounts in each direction, corresponding to the dot positions in the next and previous patterns in the same inducing sequence. These findings extend our initial report of the phenomenon of "representational momentum" (Freyd & Finke, 1984a), and help to rule out alternatives to the proposal that visual memories tend to undergo, at least to some extent, the transformations implied by a prior sequence of observed events.

We have recently found evidence that visual memory of the final position of an object is systematically distorted by a preceding series of displays that imply continuing motion of the object (Freyd & Finke, 1984a). In these experiments, subjects observed a rectangle presented at three consecutive orientations in the picture plane, implying that the rectangle was rotating about its center. They were instructed to remember the appearance of the rectangle at the third orientation. A fourth rectangle was then presented, which was either identical to the third or was rotated slightly forwards or backwards with respect to the direction of the implied angular motion. The subjects' task was to judge whether or not the last two rectangles were identical in position.

We found that the *forward* distractors were more difficult to reject than the *backward* distractors, as measured by both reaction time and error rate, even though the two types of distractors were rotated by equal amounts from the third pattern's true orientation. We referred to this effect as "representational momentum," and proposed that it resulted from a tendency for the subjects to remember the position of the final orientation as shifted in a direction consistent with the rotations implied by the preceding sequence, analogous to the tendency for a physical object to continue moving once it has been set into motion.

Our explanation for this effect is that the human mind has internalized the properties of physical momentum, with the consequence that representational momentum and physical momentum obey many of the same laws. The mechanism for representational momentum, we suggest, is the following: First, the implied motions of an object cause an observer to begin to mentally extrapolate those motions forward, into the future, with the extrapolation starting

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out as a spontaneous and automatic process. Second, the strength of this extrapolation tendency (how easily it can be suppressed or altered) is determined by the momentum associated with the implied motions. Third, we assume that cognitive effort of some kind is needed to prevent the forward extrapolation from continuing, just as an opposing force is needed to stop a physically moving object. Finally, we propose that mental extrapolation, like a moving mass, cannot be instantly halted, but rather continues for some distance beyond the point where the stopping force is applied. We believe that this is the reason why implied motions lead to small forward shifts in memory for an object's last-observed position.

According to our model, error rates and reaction times for rejecting forwardly displaced distractors will be larger than those for rejecting backwardly displaced distractors because the forward distractor positions will be harder to distinguish from the object's remembered position than the backward distractor positions. These differences should become more pronounced as the remembered position more closely approaches that of the forward distractor. In addition, reaction times and error rates for verifying the object's true final position should generally fall somewhere in between those for rejecting the forward and backward distractors, and should increase as the memory is forwardly shifted by increasing amounts.

In general, we would expect to find that any factor that influences physical momentum, such as changes in velocity or mass, would also influence representational momentum. In forthcoming studies, we have begun to test some of the specific, quantitative predictions that this model would make, such as whether the size of the effect increases linearly with increases in implied velocity (e.g., Freyd & Finke, 1984b). However, in the present study we had two other goals. The first was to try to extend the phenomenon to other types of implied physical transformations. For example, does representational momentum apply to all of the possible ways an object might be seen to move or change? Or is it specific only to the most elementary types of motion, such as simple rotation or translation? In particular, we wondered whether the momentum effect would occur even when the implied motions of individual parts or elements of a pattern were in separate directions, corresponding to a changing overall configuration. This seemed to be an interesting possibility, because previous research had shown that people can anticipate what a pattern will look like when one or more of its elements is displaced (e.g., Pinker & Finke, 1980).

Our second goal was to try to rule out certain classes of explanations of the effect. For instance, because the intervals separating the stimulus displays in Freyd and Finke (1984a) were fairly short (ranging from 250 to 750 ms) and because the effect diminished in strength as these intervals increased, we could not be sure that it was entirely independent of elementary sensory processes underlying the perception of motion. We therefore wanted to assess the possible contribution of illusions of visual "apparent motion" to the effect (e.g., Kolers, 1972; Robins & Shepard, 1977; Ullman, 1979), and to see whether it would still obtain when the inducing and retention intervals were extended beyond the range where these illusions normally occur. In addition, we wanted to rule out full extrapolation to the next logical step in the inducing sequence as an alternative explanation, which might have accounted for at least some of the results of our original study.

Experiment 1

Our decision to look at the momentum effect in the special case where a sequence of displays implied independent motions of pattern elements, depicting a changing, nonrigid form, was motivated by methodological, in addition to theoretical considerations. Displacing a rigid pattern uniformly in the same direction would be more susceptible to artifacts possibly arising from pursuit eye movements, where an observer might begin to track the pattern as it was depicted to move at a constant rate (e.g., Farrell, Putnam, & Shepard, 1984; Steinbach, 1976). This problem is largely avoided by displacing each element in a separate direction, so that judgments of equivalence can be based on apparent changes in the overall shape of the pattern.

In each of the present experiments, our stimuli consisted of simple dot patterns. In Experiment 1, we followed the general procedure for presenting the stimulus displays in

Freyd and Finke (1984a), varying the presentation rates in order to study the influences of apparent motion. We predicted that the momentum effect would diminish in strength as the intervals (ISIs) between the patterns increased, because we had found this to be true for implied rotation, but that the effect would still be present even when apparent motion could no longer be reliably produced.

Method

Subjects. Sixteen undergraduate students at the State University of New York at Stony Brook served as subjects. Their participation partially satisfied a research requirement in an introductory psychology course.

Stimuli. The dot patterns were generated, presented, and controlled using an IBM Personal Computer in conjunction with an IBM Color Display, which was mounted on a viewing platform in a separate room from where the computer and its supporting equipment were located. Each of the patterns consisted of three green dots presented within a circular viewing field 17.6° in diameter at a viewing distance of 42 cm. The individual dots were presented as single illuminated pixels in medium resolution, each having a diameter of approximately 1 mm on the display screen. The patterns were presented at the center of the viewing field and subtended an average visual angle of 4.1°. To minimize the perceptibility of phosphor persistence, the patterns were displayed against a uniform, medium grey background, which was constantly present on the screen.

Although phosphor persistence has been reported to be a potential artifact in experiments on short-term visual memory, especially in investigations of visual integration over brief periods (e.g., Irwin, Yantis, & Jonides, 1983), this does not present a problem in the present study, for several reasons. First, the IBM Color Display contains P22 phosphor, which has a decay rate ranging from 10 μs to 1 ms. Second, the presence of a residual phosphor image of the memory pattern on the screen would only serve to help the subjects to reject the distractors; and hence, would weaken any genuine momentum effects. Similarly, residual impressions of the memory pattern resulting from visual afterimages or the visual icon (Coltheart, 1980; Long, 1980; Sperling, 1960) would also make it easier to detect any differences between that pattern and the test pattern.

A typical display sequence is shown in Figure 1. Each trial began with a red fixation dot presented at the center of the screen for 2 s, accompanied by a 1-s warning tone. Following a blank interval of 1 s, the 4-dot patterns were presented in succession, separated by blank intervals of variable duration. Depending on the type of trial, the interstimulus interval (ISI) could be 250, 500, 750, or 1,000 ms. The first three patterns in the sequence, each presented for a duration of 250 ms, depicted independent motions of the dots from either of two starting configurations to a final configuration, which was the one to be remembered. The final configuration was the same for all trials in this and every other experiment, and is shown in the figure as the *memory* pattern (#3). The (*x*, *y*) coordinates of the three dots in the memory pattern, with respect to the center of the screen, were, in pixel units, (10, 10), (20, 0), and (−20, −10). The vertical height of the display field was adjusted so that 10 pixels corresponded to an angular distance of 1° along both the horizontal and vertical axes.

In the first two patterns in the sequence, which we refer to as the *inducing* patterns, the dots were located 10 and 5 pixels, respectively, from their positions in the memory pattern. For one set of inducing patterns, the dot corresponding to the topmost dot in the memory pattern was depicted as moving vertically downwards, the one corresponding to the rightmost dot was depicted as moving horizontally to the right, and the one corresponding to the leftmost dot was depicted as moving vertically upwards (see Figure 1). For the other set, the dots in the inducing patterns were displaced by the same amounts but in the opposite directions. Here, the dot corresponding to the topmost dot in the memory pattern was now depicted as moving vertically upwards; the rightmost dot, horizontally to the left; and the leftmost dot, vertically downwards. The two sets of inducing patterns therefore depicted opposite

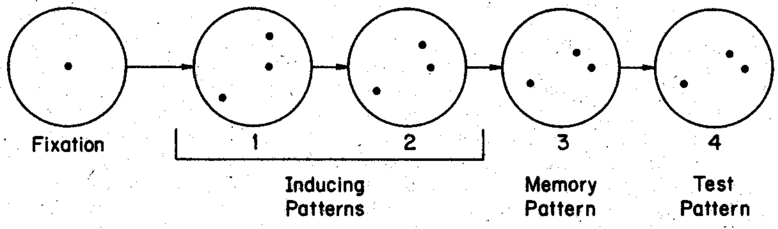


Figure 1. Example of display sequences used in practice and experimental trials. [Following a fixation display, the 4-dot patterns were presented for 250 ms each, separated by ISIs ranging from 250 to 1,000 ms. The subject's task was to remember the third pattern in the sequence (the *memory* pattern), and to judge whether or not the *test* pattern was identical to it in all respects. The first two patterns in the sequence (the *inducing* patterns) depicted independent translations of the dots. The particular inducing patterns shown were presented to half of the subjects, whereas a different set of patterns, depicting opposite motions of the dots, were presented to the other half. The test pattern in this example is identical to the memory pattern; this occurred on half of the trials. For purposes of illustration, the dots are drawn at a larger size, and within a smaller viewing field than in the actual displays (see text).]

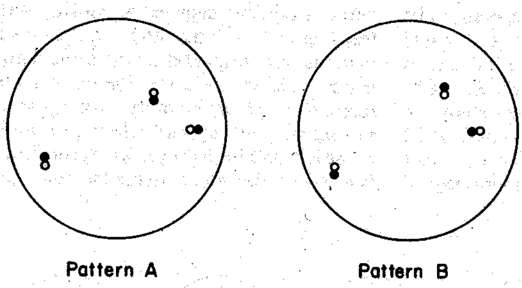
motions of the dots in achieving the final, memory configuration.[1]

There were three types of test patterns. The test pattern could be identical to the memory pattern, a *forward* distractor, or a *backward* distractor. In the forward distractors, each of the dots was displaced 2 pixels from its position in the memory pattern, in the same direction that the dots had been displaced in the two inducing patterns. In the backward distractors, the dots were displaced 2 pixels in the opposite directions. Examples of these two types of distractors are shown in Figure 2. Because opposite implicit motions were created by the two sets of inducing patterns, the forward distractor for one set was physically identical to the backward distractor for the other set, and vice versa. On every trial the test pattern was displayed for 3 s, and was followed by a 4-s intertrial interval.

The selection of these particular inducing and test patterns was made on the basis of pilot studies, which suggested that the forward distractors would produce moderate error rates and elevated reaction times with these displacement magnitudes. We therefore designed the task to be moderately difficult, but not so difficult that subjects would never be able to make the discriminations.

The selection of the particular range of ISIs was made on the basis of similar pilot work regarding the presence and quality of sensations of apparent motion. At the shortest ISI of 250 ms, smooth apparent motion between the corresponding dots was experienced quite easily. At the 500 ms ISI, sensations of apparent motion were weaker, but still present. At the longer ISIs of 750 and 1,000 ms, apparent motion was experienced only rarely, although one could still tell that the displays represented a moving configuration of dots. These observations were obtained using a simple rating scale.[2]

Procedure. The subjects were tested individually, and the experiment lasted approximately 1 hr. At the beginning of the experiment, the subjects were seated in front of the Color Display and were told that they would be asked to judge dot patterns presented at the center of the screen, which they were to observe by looking through a viewing aperture. The structure of the display sequences, and the nature of the task, were then explained. Specifically, the subjects were told that they were always to watch each of the 4 patterns in the sequence, and then to judge whether or not the last pattern was identical, in all respects, to the one that immediately preceded it. They were to make these judgments by pressing either a *yes* or *no* button on a response box located directly below the display. The instructions emphasized maintaining constant eye fixation at the center of the screen throughout the presentation sequence, and watching all three dots at once in each pattern, as opposed to looking at any particular dot.


Pattern A

Pattern B

Figure 2. The two test patterns serving as *distractors* in all practice and experimental trials (closed circles), shown in relation to the memory pattern (open circles). [For the particular display sequence depicted in Figure 1, Pattern A functioned as the *forward* distractor (because, in this case, the dot displacements are consistent with those in the inducing patterns), and Pattern B functioned as the *backward* distractor. For the other inducing sequence, where opposite motions were implied, Pattern A served as the backward distractor and Pattern B as the forward distractor; this controlled for possible differences in perceived similarity between these two patterns and the memory pattern. As in Figure 1, dot size and position relative to the viewing field are exaggerated for clarity.]

A demonstration program was then presented, in which two examples of sequences using each type of test pattern were shown. As the subject observed these displays, the experimenter explained the two ways in which the last two patterns could be different, calling attention to the distinction between the forward and backward distractors, and emphasizing that both types of distractors were to be regarded as different from the third pattern. For these demonstration trials, an ISI of 625 ms was used, which was the average ISI for the experimental trials.

A practice session consisting of 32 trials was then conducted, using ISIs of 250, 500, 750, and 1,000 ms in blocks of 8 trials. The instructions stressed both speed and accuracy and pointed out that although the presentation rates would sometimes vary, the subjects were always to base their judgments on whether the last two patterns appeared to be identical.

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[1] These inducing displays were normally seen as three independently moving dots, or as a triangle undergoing a change in shape. The changing configuration of dots could also correspond, in principle, to changes in the position of a rigid triangle moving in three-dimensional space (e.g., Johansson, 1975; Shepard, 1981). This was seldom seen, however, for the displaced dots did not reprsent a consistent three-dimensional transformation of the triangle's position across the inducing displays.

[2] The scaling procedures for obtaining judgments of the quality of apparent motion were similar to those used by Freyd (1983b). Five observers who were familiar with the technique of magnitude estimation were presented 24 stimulus sequences consisting of the first three patterns. Each pattern was shown for 250 ms, using ISIs of 250, 500, 750, and 1,000 ms. Equal numbers of each ISI were randomly ordered in three blocks of 8 sequences, with the first block counting as practice. The observers made their judgments of the goodness of apparent motion in each display using a 4-point scale, in which a rating of 4 corresponded to *good, continuous apparent motion;* 3 corresponded to *weak, continuous apparent motion;* 2 corresponded to *weak, discontinuous apparent motion;* and 1 corresponded to *no apparent motion at all.* The mean ratings for the displays at these ISIs were, respectively, 3.7, 2.7, 1.6, and 1.1. Each observer rated the quality of apparent motion as decreasing with increasing ISI, and only one observer ever reported seeing apparent motion at the longest ISI of 1,000 ms.

For each block of trials, there were equal numbers of trials in which the last two patterns were the same, and in which the last two patterns were different. For the *different* trials, there were equal numbers of forward and backward distractors. The order in which the trials were presented was randomized, with the single constraint that the same type of test pattern did not occur on more than three consecutive trials. The subjects were provided with this information at the start of the practice session, and were reminded that they should expect to see an equal number of *same* and *different* trials, along with an equal number of forward and backward distractors, and that they should not try to anticipate or guess which type of trial would come up next. The experimenter also instructed the subjects to continue looking into the viewer until the session was concluded.

To remind the subjects when to respond, a faint audible *click* was presented in conjunction with the onset of the test patterns. Feedback was provided after each response, in the form of a message indicating *error* or *correct* displayed at the center of the screen. The subjects were told not to worry if they started out making quite a few errors, because the task would be difficult and it would take a little practice to learn to make these judgments. The importance of responding both quickly and accurately was, however, again emphasized.

The practice trials were followed by 128 experimental trials, presented in 4 sets of 32 trials each. The order of the different ISI blocks within each set was varied using a Latin square. As in the practice session, there were equal numbers of same and different trials, as well as equal numbers of forward and backward distractors in the different trials. The procedure for presenting the experimental trials was similar to that for the practice trials, except that error feedback was no longer given. The subjects were informed of this prior to the start of the trials, and they were again reminded to respond as quickly and as accurately as they could. Between the sets of trials, they were provided with a 1-min rest period.

Each subject was shown the same inducing patterns on every trial, with the selection of inducing patterns, and hence, with the direction of implicit motion counterbalanced between the subjects, providing a control for possible differences in discriminability between the particular patterns used as the forward and backward distractors.

Reaction times and errors for the experimental trials were recorded onto a data file. The experimenter monitored the equipment during the experimental and practice trials, and was never in contact with the subject throughout these times. The overhead room lights were kept on dim when the instructions were given, and were turned off during testing. At the end of the experiment, the subject was interviewed, and was then debriefed regarding the purpose of the experiment and the predicted results.

Results

Separate analyses of variance were conducted for errors and reaction times, and for the *same* and *different* test patterns. Because in this experiment, and in all other experiments in this study, there were no differences between the two directions of implied motion, the data are averaged across the two groups of subjects counterbalancing this factor. Reaction times greater than 3,000 ms or less than 100 ms were not included in the analyses; these occurred on fewer than 0.5% of the trials.

Table 1
Experiment 1: Mean Error Rates (Percentage) and Reaction Times (in Milliseconds) for Correct Responses

Pattern ISI	Backward distractor	Same test pattern	Forward distractor
	Error rates		
250	3.1	19.1	34.4
500	3.9	15.6	47.7
750	4.7	21.1	55.5
1,000	3.9	18.0	57.8
	Reaction times		
250	702	730	868
500	704	723	924
750	742	792	990
1,000	787	796	980

Note. For each measure and ISI, the data for the forward and backward distractors are based on 128 observations, and the data for the *same* test pattern on 256 observations; $N = 16$.

Errors. The mean error rates for each ISI and test pattern are presented in the top of Table 1. Error rates for the distractors, in the outer two columns, refer to the incorrect *same* judgments, whereas those for the same test patterns, in the center column, refer to the incorrect *different* judgments. The overall average error rate for rejecting the forward distractors, 48.8%, was significantly greater than that for rejecting the backward distractors, 3.9%, $F(1, 15) = 68.20$, $MS_e = 6.06$, $p < .001$. This effect of distractor type on error rate was shown individually by each of the 16 subjects, and thus, indicated a robust momentum effect. In contrast to our initial expectations, the error rates for the distractors increased, on the average, with increasing ISI, $F(3, 45) = 5.73$, $MS_e = 1.10$, $p < .01$, whereas the difference between the forward and backward distractor error rates also increased with increasing ISI, as revealed by a significant interaction between ISI and the type of distractor, $F(3, 45) = 5.29$, $MS_e = .98$, $p < .01$.

Analyses of simple effects showed that the increase in error rate with increasing ISI was specific to the forward distractors, $F(3, 45) = 6.57$, $MS_e = 1.74$, $p < .01$, as the effect of ISI on error rate for the backward distractors was not significant, $F(3, 45) = .12$, $MS_e = .34$. Further analyses of simple effects showed that the forward–backward difference was reliable at each level of ISI (for all tests, $p < .001$).

An analysis of variance on error rates for the *same* test patterns showed no effect of varying the ISI, $F(3, 45) = .52$, $MS_e = 4.11$, as is also apparent from inspection of Table 1. These error rates averaged 18.4%, falling between the averages for the two types of distractors.

The error rates averaged 20, 25, 22, and 23%, respectively, across the 4 blocks of trials, $F(3, 45) = 2.20$, $MS_e = 3.51$, $p > .10$, providing no evidence for a practice effect.

Reaction times. In agreement with the results for error rates, the mean reaction times for correctly rejecting the forward distractors were significantly greater than those for correctly rejecting the backward distractors, $F(1, 15) = 39.71$, $MS_e = 34{,}369$, $p < .001$, and increased, on the average, with increasing ISI, $F(3, 45) = 4.87$, $MS_e = 13{,}691$, $p < .01$. However, there was no interaction between ISI and distractor type, $F(3, 45) = .59$, $MS_e = 17{,}179$. These results are presented in the bottom of Table 1. The average difference in reaction time between the forward and backward distractors was 207 ms, and the forward–backward difference was shown individually by 15 of the 16 subjects.

An analysis on the reaction times for correctly responding to the *same* test patterns showed that these times, like those for rejecting the two types of distractors, increased with increasing ISI, $F(3, 45) = 4.78$, $MS_e = 5{,}205$, $p < .01$.

Although not formally analyzed, the reaction times for trials on which the response *same* was incorrectly given to the forward distractors were examined to determine whether these errors could be attributed to rapid, anticipatory *same* responses. For levels of ISI increasing from 250 to 1,000 ms, these reaction times averaged 725, 852, 891, and 944 ms, respectively, and thus increased along with the increasing error rates, and were generally longer than the reaction times for correctly responding to the actual *same* patterns.

Reports by subjects. When interviewed at the conclusion of the experiment, all of the subjects claimed that they had followed the instructions for observing and judging the dot patterns. In addition, all reported that they had found it much more difficult to detect the forward distractors, in agreement with the experimental results. Indeed, several of these subjects expressed puzzlement over not having "seen" more forward distractors, because they had been led to expect that there would be an equal number of forward and backward distractors. Also, although some of the subjects reported that they had attended to only two of the three dots, none reported having singled out and watched just one of the dots during the display sequences.

Discussion

In this first experiment, forward distractors were much more difficult to reject than backward distractors, as indicated by large, reliable differences in both error rate and reaction time. We interpret these findings as evidence that small forward shifts in visual memory can be induced by presenting, in advance, a sequence of displays implying that objects in a configuration are undergoing independent translations; and thus that the phenomenon of representational momentum that we previously obtained for implied rotations of geometric forms (Freyd & Finke, 1984a) may be extended to more complex types of implied transformations.

An unexpected difference between the present findings and those we had obtained for implied rotation is that the momentum effect in this case appears not to diminish in strength as the pattern ISI increases. On the contrary, there was a significant increase in the strength of the effect with increasing ISI, in terms of the distractor error rates, which corresponded to a decrease in the quality of apparent motion. Evidently, visual sensations of motion, if anything, are associated with a reduction in the momentum effect established under these conditions.

These findings also tend to rule out other types of sensation-based accounts of the effect. As discussed previously, any lingering sensory impression of the memory pattern, whether resulting from an afterimage, an icon, or artifactual persistence of the CRT, would serve to inhibit the effect. In any case, such sensations would generally decrease, not increase in strength over time. In addition, motion aftereffects could not be observed in any of the test patterns; and, had they appeared in the memory pattern, they would have been in the direction opposite the inducing motion, resulting in a backward memory shift (e.g., Anstis & Moulden, 1970; Cavanaugh & Favreau, 1980; Favreau; 1976). These findings, therefore, do not seem to be explainable in terms of any of the usual characteristics of stimulated or adapted motion-detecting mechanisms (see, in particular, Pantle, 1978; Sekuler, 1975; Sekuler & Levinson, 1977).

Certain other aspects of our present experimental methods and results further speak to the robustness of this effect. First, unlike our previous study, subjects were given error feedback during the practice trials. Second, the memory pattern was exactly the same for all practice and experimental trials; yet there was no evidence for any improvement in performance across the trials. Third, had the subjects tried to "cheat" in any way by not looking at the inducing displays, this would only have served to reduce the effect. And finally, the correspondence between increases in reaction time and error rate argue against any kind of speed–accuracy trade-off account of the results.

In the next two experiments, we take up the question of why we did not find a reduction in the strength of this momentum effect as the ISIs were increased.

Experiment 2

Although the absence of a reduction in the effect with increasing ISI in Experiment 1 is an interesting result, in that it strongly suggests that the effect is not mediated by normal sensory processes, we still need to establish why this is so. For instance, it may be that decreasing the implied velocity in this case, by increasing the inducing ISI, has little influence on the momentum effect. It may also be that the effect does not decay (or, possibly, that it increases) as the retention interval increases. In the procedure of the first experiment, as in Freyd and Finke (1984a), the ISIs between the inducing patterns, the memory pattern, and the test pattern were the same on any trial, and hence the possible effects of the implied velocity of the inducing displays were always confounded with those of the length of the retention period.

Experiments 2 and 3 examined these two factors separately. In Experiment 2, the ISIs between the two inducing patterns and the memory pattern were varied, while keeping the ISI between the memory pattern and the test pattern constant, in an attempt to isolate the effects of implied velocity from those of retention duration. Also, we extended the range of inducing ISIs to 2 s, to permit a more critical test of the proposal that the momentum effect for these displays is not dependent on sensory processes underlying motion perception.

Method

Subjects. As in Experiment 1, the subjects consisted of 16 undergraduates at the State University of New York at Stony Brook, who participated in order to partially satisfy a research requirement in an introductory psychology course. None of the subjects had participated in the previous experiment.

Procedure. The procedure of Experiment 1 was followed exactly, with the exception of these four changes: (a) The retention interval (i.e., the interval between the offset of the memory pattern and the onset of the test pattern), instead of being varied, was a constant 500 ms for all trials. (b) The ISIs between the first three patterns were varied as before, except that the size of each interval was now doubled, resulting in ISIs of 500, 1,000, 1,500, and 2,000 ms. (c) In the demonstration program, the inducing ISI was 1,250 ms, which was the average of the increased experimental ISIs. (d) The subjects were now informed that although the presentation rates for the first two patterns may vary, the interval between the last two patterns would always remain the same.

Results

Errors. The mean error rates for each condition are presented in the top of Table 2. As in the previous experiment, there were substantially more failures to reject the forward distractors than the backward distractors, $F(1, 15) = 53.83$, $MS_e = 5.57$, $p < .001$, and this difference, as measured by the error rates, was again shown individually by all 16 subjects. The overall effect of increasing the inducing ISIs, however, was not significant, $F(3, 45) = 1.62$, $MS_e = 1.04$, $p > .10$. The mean error rates for each condition are presented in the top of Table 2.

Inspection of this table suggests that the forward–backward difference in error rate decreases as the inducing ISI increases. However, a test of the interaction between ISI and type of distractor was only marginally significant, $F(3, 45) = 2.29$, $MS_e = 1.33$, $p < .10$. Analysis of simple effects showed a marginally significant effect of ISI on the forward distractor error rates, $F(3, 45) = 2.22$, $MS_e = 2.06$, $p < .10$, and no effect of ISI on the backward distractor error rates, $F(3, 45) = .58$, $MS_e = .32$. Additional analyses showed that the forward–backward difference was again reliable at each level of ISI (for all tests, $p < .001$).

Error rates for the *same* test patterns showed no effect of varying the inducing ISI, $F(3, 45) = .98$, $MS_e = 2.13$. These error rates averaged 19.9%, and, as in Experiment 1, fell between those for the two types of distractors.

Reaction times. The only significant effect on reaction time was that the forward distractors took longer to reject (by an average of 248 ms) than the backward distractors, $F(1, 15) = 77.61$, $MS_e = 25{,}407$, $p < .001$ (see Table 2). This effect, like that for error rate, was shown by all 16 subjects. For all other analyses on reaction time, $F < 1$.

Reports of subjects. All of the subjects again claimed that they had performed the task as instructed, having regarded both the forward and backward distractors as different from the memory pattern, and that the forward distractors had seemed more difficult to detect than the backward distractors. They also reported that they had found it harder to maintain their attention when the presentation rates were very slow.

Table 2
Experiment 2: Mean Error Rates (Percentage) and Reaction Times (in Milliseconds) for Correct Responses

Inducing ISI (ms)	Backward distractor	Same test pattern	Forward distractor
	Error rates		
500	3.9	19.5	50.0
1,000	3.1	17.2	46.9
1,500	4.7	22.7	36.7
2,000	6.3	20.3	37.5
	Reaction times		
500	766	889	1,004
1,000	775	836	1,030
1,500	765	848	1,002
2,000	758	883	1,022

Note. For each measure and ISI, the data for the forward and backward distractors are based on 128 observations, and the data for the *same* test pattern on 256 observations; $N = 16$.

Discussion

The results of Experiment 2 suggest that our momentum effect is relatively insensitive to changes in the implied inducing velocities, at least within this range of ISIs. There is some suggestion in the data that the error rate difference diminishes slightly as the inducing ISI increases from 500 to 2,000 ms, although this effect is only marginally significant, and is not shown in the reaction time data.

Why does the momentum effect remain fairly stable, even when the inducing ISIs are increased by a factor of four? One reason may have to do with the relatively small size of the displacements used in the inducing patterns. Because for each step in the inducing sequence the dot displacements subtended 0.5° of visual angle, the implied velocities of the dots (counting the 250 ms stimulus durations) were actually quite small, ranging from 0.2 to 0.7°. Larger displacement magnitudes in the inducing patterns may therefore be needed to obtain velocity effects for these types of implied transformations.

Freyd and Finke (1984b) found a velocity effect, on errors, for implied rotation, in which the inducing ISIs ranged from 100 to 900 ms, and in which the retention ISI was a constant 250 ms. However, this effect was obtained only by using a wide range of displacement magnitudes in the distractors; and, although significant, was not very large. Accordingly, one may need to use a greater range of distractors to obtain significant velocity effects under the present inducing conditions.

The relative absence of an effect of inducing velocity does, however, further reduce the likelihood that the momentum effect can be attributed to sensory processes underlying perceived motion. At the longest ISIs of 1,500 and 2,000 ms, where the momentum effect is still robust, apparent motion is simply not experienced. Observers report that they merely "know" that the inducing displays are depicting a moving configuration of dots, without really "seeing" any motion. Thus, although the depicted transformations may in some sense be regarded as "perceived," the perceptual experience may not properly be described in terms of genuine sensations of movement (cf. Gibson, 1966, 1979).

Eventually, we would expect the momentum effect to diminish in strength as the inducing ISIs were further increased, because, in the limiting case, the implied velocity would be reduced to zero. It is probably not feasible to use the present methods to examine the effects at much longer ISIs, however, due to practical constraints on the length of time subjects can attend to the entire sequence of displays.

Experiment 3

Whereas Experiment 2 examined the effect of varying the inducing ISI at a constant retention ISI, Experiment 3 examined the effect of varying the retention ISI with the inducing ISI held constant.

There are three outcomes that would be of theoretical interest. First, the momentum effect could decay as the retention interval increased. This would imply that representational momentum is a short-lived phenomenon, without serious implications for the long-term retention of visual information. Second, the effect could remain stable over a range of retention intervals, as would be revealed by a constant difference in error rates and reaction times for judging the forward and backward distractors. This would imply that representational momentum has a lasting influence on visual memory, but that it can be stopped soon after it occurs. Third, the effect might continue to grow in strength as the retention period increases, suggesting that representational momentum cannot be stopped very quickly. Experiment 3 was designed to distinguish among these three possibilities.

Method

Subjects. Sixteen new subjects were selected as in the first two experiments.

Procedure. The procedure of Experiment 1 was this time modified in the following four ways: (a) A constant inducing ISI of 1,000 ms was used in every trial. (b) The retention ISIs, which were twice as long as those in Experiment 1, consisted of 500, 1,000, 1,500, and 2,000 ms. (c) In the demonstration program, the retention ISI was 1,250 ms, the average of the retention intervals used in the new experimental trials. (d) The subjects were informed that the presentation rate for the first two patterns would always be the same, but that the interval between the last two patterns would vary.

Table 3
Experiment 3: Mean Error Rates (Percentage) and Reaction Times (in Milliseconds) for Correct Responses

Retention ISI (ms)	Backward distractor	Same test pattern	Forward distractor
	Error rates		
500	4.7	18.3	36.7
1,000	10.9	20.7	43.0
1,500	11.7	22.2	43.7
2,000	15.6	19.9	47.7
	Reaction times		
500	795	869	888
1,000	791	839	968
1,500	904	925	931
2,000	897	987	992

Note. For each measure and ISI, the data for the forward and backward distractors are based on 128 observations, and the data for the *same* test pattern on 256 observations; $N = 16$.

Results

Errors. As shown in Table 3, more errors were again made in rejecting the forward distractors than in rejecting the backward distractors, $F(1, 15) = 51.12$, $MS_e = 4.11$, $p < .001$, and this difference was shown individually by all 16 subjects. There was also a significant overall effect of increasing the retention interval on error rates for the distractors, $F(3, 45) = 3.02$, $MS_e = 1.39$, $p < .05$. These two effects, type of distractor and retention ISI, did not interact, $F(3, 45) < .10$, $MS_e = 1.38$. The difference in error rates between the forward and backward distractors averaged 32% across levels of retention ISI, and was significant at each of these levels ($p < .001$).

Error rates for responding to the *same* test patterns did not vary with the retention ISI, $F(3, 45) = .40$, $MS_e = 2.72$, and averaged 20.3%.

Reaction times. The pattern of reaction times for correct rejection of forward and backward distractors corresponded to that for error rates, although at lower levels of significance. The forward distractors took longer to reject than the backward distractors, $F(1, 15) =$

15.30, $MS_e = 19{,}984$, $p < .01$, although there was a marginally significant increase in these reaction times with increasing retention ISI, $F(3, 45) = 2.63$, $MS_e = 24{,}405$, $p < .10$. Here, too, there was no interaction between type of distractor and ISI, $F(3, 45) = 2.14$, $MS_e = 13{,}988$, $p > .10$ (see bottom of Table 3). The difference between the reaction times for rejecting the forward and backward distractors averaged 98 ms, and was shown individually by 13 of the 16 subjects.

Reaction times for correctly responding to the *same* test patterns did, however, increase with increasing retention ISI, $F(3, 45) = 6.12$, $MS_e = 11{,}070$, $p < .01$, as is also shown in Table 3.

Reports of subjects. Not surprisingly, the subjects generally reported that the task became more difficult as the retention interval increased. Several of the subjects reported that they actively attempted to visualize the memory pattern on those trials for which the retention interval was longest (2,000 ms), as might be expected from current studies on the amount of time it takes to form visual images (e.g., Kosslyn, Reiser, Farah, & Fliegel, 1983). However, the opportunity to form such images evidently did not reduce the memory distortions, because the forward–backward differences in error rate and reaction time were consistent across all of the retention intervals.

Discussion

The results of this experiment indicate that the momentum effect reaches its maximum size within 500 ms, and then remains relatively stable. Increasing the retention interval to 2 s resulted in equivalent increases in error rates for judging the forward and backward distractors, and similarly for reaction times, with no hint of any interaction that might suggest an increase or a decay in the strength of the effect. Rather, increasing the retention interval made both types of distractors harder to judge.

Comparing the results of Experiments 2 and 3 with those of Experiment 1 suggest that the effect of varying the inducing and retention ISIs is not simply additive. In Experiment 1 we found that the forward–backward difference in error rate increased as the inducing and retention ISIs increased together, and in Experiment 2, this difference decreased marginally as the inducing ISI increased with a constant retention ISI. If these two factors were independent, one would have expected to find an increasing difference in these error rates as the retention ISI increased with a constant inducing ISI.

The fact that we did not suggests that the task of rejecting the forward distractors is harder when the inducing and retention intervals are the same. In further support of this proposal, the differences in error rate between the forward and backward distractors were larger in Experiment 1 than in either of our other two subsequent experiments (compare Tables 1, 2, and 3). A possible reason for this is that when the inducing ISIs always match the retention ISIs, subjects may begin to anticipate seeing the next display that would follow after the memory pattern in the same inducing sequence. This possibility, which presents a potential problem for our study, is addressed in Experiment 4, along with related concerns.

Experiment 4

The primary goal of this experiment was to distinguish between a momentum account of the previous results, and that in which an observer anticipates seeing the next configuration in the sequence. The momentum account explictly assumes that people are trying *not* to extrapolate forward in this task. To give an analogy, suppose you were driving your car and suddenly decided to stop. Once you apply the brakes, your car continues to move forward for some distance, until friction is sufficient to counteract the momentum. The forward displacement of the car from the intended stopping position would correspond, in the momentum model, to the forward transformation of a visual memory; each occurs to some degree, despite efforts to the contrary, with the amount of displacement depending on how well the "brakes" work. Assuming that at least some resistant force can be applied, the forward displacement will never be as large as that for the unconstrained continuation.

Although this might be regarded as partial extrapolation in some sense, we would like to rule out a specific kind of extrapolation model—one in which a subject might infer the next logical position in a more discrete fashion.

For example, if you heard someone call out the numbers *1, 2, 3,* and *4,* you would probably think of the number *5* as a result of having formed some kind of mental "set" or "schema" (cf. Haber, 1966; Neisser, 1976). To return to the car analogy, this would be like forgetting to apply the brakes, and allowing the car to move forward at the same rate as before. In the previous experiments, because the forward distractors were physically closer to these extrapolated configurations than the backward distractors, this account would also predict that they would tend to be judged more often as equivalent to the memory pattern.

A related alternative is that the subjects might be biased to respond *same* whenever any forward motion is depicted in the test patterns. This could arise from the way subjects might interpret the function of the inducing displays or, as a less likely possibility, from having misunderstood the instructions, believing that they were to respond *same* to any of the forward distractors.

In this experiment, the displacement magnitudes for the forward and backward distractors were increased so that they were now identical to the displacement magnitudes used in the inducing displays. Hence, the forward distractors now represented the next full step in the inducing sequence, whereas the backward distractors represented the previous step, and were thus identical to the second inducing pattern. We predicted that the momentum effect should be much weaker in this case, assuming that representational momentum can be stopped fairly quickly, because the forward distractors would no longer correspond to small forward transformations of the memory pattern. The alternative accounts just mentioned would make the opposite prediction, that the momentum effect should be even stronger, because the forward distractors would now correspond precisely to the forwardly extrapolated configurations.

Method

Subjects. Sixteen new subjects were selected as in the previous experiments.

Procedure. The procedure of Experiment 1 was repeated, with the single exception that the displacement magnitude for dots in the forward and backward distractors was increased from 2 to 5 pixels (0.5 degrees). Thus, the forward distractors were now the configuration of dots in the next step in the inducing sequence, and the backward distractors were now the configuration of dots in the previous step in the sequence.

Table 4
Experiment 4: Mean Error Rates (Percentage) and Reaction Times (in Milliseconds) for Correct Responses

Pattern ISI (ms)	Backward distractor	Same test pattern	Forward distractor
	Error rates		
250	1.6	3.5	1.6
500	0.8	2.3	4.7
750	0.8	2.7	3.1
1,000	1.6	3.1	4.7
	Reaction times		
250	615	604	630
500	631	596	678
750	664	651	694
1,000	696	668	710

Note. For each measure and ISI, the data for the forward and backward distractors are based on 128 observations, and the data for the *same* test pattern on 256 observations; $N = 16$.

Results

Errors. As Table 4 shows, each of the error rates was below 5%. An analysis of variance indicated that the error rates for failing to reject the forward and backward distractors were not significantly different, $F(1, 15) = 2.74$, $MS_e = .41$, $p < .10$. Additional analyses showed that there were no effects of varying the ISIs on error rates for any of the test patterns (for all analyses, $F < 1$).

Reaction times. As for the error rates, there was not a significant difference between reaction times for rejecting the forward and backward distractors, $F(1, 15) = 1.28$, $MS_e = 17{,}507$, $p > .10$. Reaction times did increase, on the average, with increasing ISI, both for the distractors, $F(3, 45) = 4.68$, $MS_e = 8{,}087$, $p < .01$, and for the *same* test patterns, $F(3, 45) = 4.90$, $MS_e = 4{,}063$, $p < .01$. Distractor type and ISI did not interact, $F(3, 45) = .53$, $MS_e = 3{,}765$. The bottom of Table 4 presents the mean reaction times for all conditions.

Reports of subjects. As expected, the subjects all found the task to be easy, as supported by their error rates and reaction times. None reported having found the forward distractors in this case difficult to reject.

Discussion

The absence of a significant momentum effect under these conditions shows that our previous results cannot be explained in terms of expectations for seeing the next logical step in the display sequence, or in terms of a general bias to regard all forward distractors as equivalent to the memory pattern. Rather, these findings support the prediction of our momentum model that forward distractors should be much harder to reject than backward distractors only when they correspond to small forward transformations of the memory pattern, as in the previous three experiments.

It is, of course, possible that we have made a Type II error in our present analyses, because the obtained differences in error rate and reaction time between the forward and backward distractors, although small and not significant, were still in the direction predicted for the momentum effect. It is not necessary, however, that we fully accept the null hypothesis here in order to rule out these alternatives, because they would have predicted effects at least as large as those in the previous experiments. Moreover, according to our momentum model a diminishing but finite difference should remain, theoretically, as the forward and backward distractor displacements are increased, because the forward distractors would become progressively easier to distinguish from the memory pattern, but never as easy as the backward distractors.[3]

The failure to find a robust momentum effect in the present case does not mean that people cannot extrapolate forward whenever the inducing sequence implies a physical transformation. For indeed, there is an extensive literature demonstrating that when the task demands that they do so, people can perform a variety of extrapolations based on implied translations and rotations (e.g., Cooper, 1976; Finke & Pinker, 1983; Rosenbaum, 1975; Shepard & Cooper, 1982). What the results of our experiments imply is that even when these extrapolations are discouraged, they still occur to a small extent, resulting in small forward shifts in memory for final position—though they do not extend completely forward to the next logical step.

The results of Experiment 4 also rule out any account based on the subjects' having confused the memory pattern with one of the inducing patterns, or on the possible "masking" of the memory pattern by the inducing patterns (e.g., Potter, 1976). In this experiment, the backward distractors were always identical to the second inducing pattern, but like the forward distractors, were easily rejected. Indeed, such accounts would make the prediction that the backward distractors would be harder to reject than the forward distractors, contrary to our results. A similar argument can be made against accounts proposing that the inducing and memory patterns might be "averaged" in memory (see Jenkins, Wald, & Pittenger, 1975; Leibrich & White, 1983), or that the inducing displays would "prime" the subjects to expect to see the initial dot configurations (e.g., Beller, 1971; Posner & Boies, 1971).

General Discussion

The present set of findings demonstrate that the remembered appearance of a pattern can be altered by presenting, in advance, a sequence of displays implying that the elements of the pattern are moving. The induced change in memory is in the direction of the implied motions, as revealed by large, consistent differences in the ease of rejecting distractors that depict the elements as displaced slightly forwards, as opposed to slightly backwards from their positions in the memory pattern. These shifts in visual memory appear to be quite robust, with little evidence of decay as the inducing and retention intervals increase from 250 ms to a full 2 s.

In several respects, this version of the momentum effect is more striking than that which we reported previously for the implied rotation of geometric forms (Freyd & Finke, 1984a). First, it appears to be much more stable over

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[3] We would also predict that if the displacement magnitudes in the distractors were reduced by increasing amounts, subjects would, ultimately, be more likely to accept the forward distractors as *same* than the actual same patterns. We did not attempt to do this in the present study, because we felt that the subjects might become frustrated after receiving error feedback following attempts to make these more difficult discriminations. However, we have recently found this kind of result in experiments on implied rotation where the displacement magnitudes for the distractors were varied parametrically (Freyd & Finke, 1984b).

a broader range of ISIs. Second, it persists even when error feedback is used in the training procedures, and the memory pattern is unchanged throughout the experiment. And third, it seems less likely to have resulted from sensory processes underlying the perception of motion.

Although it is conceivable that sensory processes may still contribute in some way to this effect, we know of no sensation-based account that would have predicted the results of our experiments. As we have argued, our momentum effect could not easily be explained in terms of apparent motion, motion aftereffects, or pattern afterimages. We have also been able to rule out alternative explanations such as speed–accuracy trade-offs, mental extrapolation to the next full step in the inducing sequence, a bias to expect forward motion, confusion between the inducing and memory patterns, and the failure to completely understand the experimental instructions. After considering the predictions that these various accounts would make, we conclude that our experimental findings are best explained in terms of a cognitive process in which visual memories are shifted forward by small amounts in the act of stopping the spontaneous extrapolation of implied motions, in a manner analogous to the way a physical object continues to move for a short distance before it can be brought to a complete stop. No other single explanation seems more consistent with the present set of results, along with those of Freyd and Finke (1984a, 1984b), and with the subjective impressions of our observers.

These findings have a number of implications for theories of how memories can change. First of all, they show that distortions in visual memory can be induced within relatively brief retention periods. Most previous research has found that visual memories are distorted following the long-term retention of information (e.g., Allen, Siegel, & Rosinski, 1978; Bartlett, 1932; Friedman, 1979; Goldmeier, 1982; Tversky, 1981). Second, these findings show that changes in visual memory can occur even when people are motivated not to allow their memories to be altered in any way. Hence, they are less susceptible to demand characteristics, experimenter bias, or other similar artifacts that frequently create problems in visual memory research (see Bekerian & Bowers, 1983; Loftus, Miller, & Burns, 1978; Weinberg, Wadsworth, & Baron, 1983). Third, they show that highly specific changes in visual memory can be induced, changes which are not easily attributed to more traditional processes such as interference, elaboration, and reorganization (e.g., Bower, 1970; Bransford & Franks, 1971; Neisser, 1967, 1982).

Our findings also have implications for theories of how people imagine transformations of objects (e.g., Cooper & Shepard, 1973; Shepard & Cooper, 1982; Shepard & Metzler, 1971). In particular, they suggest that it might not be possible to instantly halt an imagined transformation once the process has begun. Although we do not yet have direct support for this proposal, it would help to explain a puzzling finding in a study on imagined rotation by Pinker and Finke (1980). They asked subjects to judge how an array of objects would appear after it was imagined to rotate through some designated angle. These judgments were distorted in such a manner as to suggest that the subjects had imagined the array to rotate slightly beyond the point where they were supposed to stop. In light of the present findings, we suggest that the errors in judging the future appearances of objects in the Pinker and Finke study were a result of the same momentum tendency.

Another implication of our findings is that because these effects were established using essentially static stimulus displays, they suggest, in support of other recent findings, that movement can influence how we perceive or remember things, even when it is merely inferred (e.g., Friedman & Stevenson, 1980; Shepard, 1981). For example, Freyd (1983a) and, more recently, Babcock and Freyd (1984) have demonstrated that the recognition of handwritten characters is determined partly by the drawing method that observers believe led to their construction. In addition, Freyd (1983b) has found that people tend to remember the action in a still photograph as having continued further ahead in time. We therefore propose that information about movement can influence visual memories regardless of whether motion is actually seen, as long as the information is sufficient to specify which motions are likely to occur.

We should also comment on some of the shortcomings of these experiments as they relate to our momentum model. Although the major prediction that forward distractors should be much harder to reject than backward distractors for relatively small distractor displacements was supported, other, more subtle predictions were not. For example, our model predicts that reducing the implied velocity of the inducing displays should reduce the size of the momentum effect, but in Experiment 2 this was obtained only for the difference in error rate between the forward and backward distractors, and then only with marginal significance. Also, in the first three experiments error rate and reaction time differences between the distractors did not always correspond as the ISIs were varied, nor were these differences reliably associated with effects on reaction time and error rate for verifying the *same* test patterns. We believe these shortcomings reflect a lack of sensitivity in our present measures, rather than a failure of the model. Presently, we are completing another series of experiments, using more sensitive methods, to better test some of the quantitative predictions that our model makes about how the momentum effect should change with changes in the implied motions.

Finally, we should mention a potential limitation of our model in light of recent findings by McCloskey and his colleagues. Their studies have shown that people often have mistaken notions about how objects would continue to move after forces constraining their motion are removed (e.g., McCloskey & Kohl, 1983). For example, people frequently believe that a ball traveling inside a curved tube will continue to move along a curved trajectory even after it emerges—when the constraining forces no longer exist (see also McCloskey, Caramazza, & Green, 1980). These misconceptions about the principle of inertia seem contrary to our view that representational momentum accurately reflects physical momentum, and it would thus be interesting to examine how representational momentum behaves when the inducing displays depict movement under constraint.

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