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Representational Momentum

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In this study we attempted to measure changes in the mental representation of a visually presented pattern induced by a prior sequence of static displays. In Experiment 1 we showed subjects a static rectangle at three orientations along a possible path of rotation, each orientation being separated temporally with an interstimulus interval (ISI) of 250 ms. They were instructed to remember the third orientation in the sequence and were then presented with a rectangle at a fourth orientation that was either the same as, or different from, the third. There were two ways the orientation could be different: It could be a small rotation in the same direction as the implicit motion or an equally small rotation in the opposite direction. Subjects found it much harder to detect differences in the direction of implicit motion, suggesting that their memory for the third orientation had been distorted along that direction. In Experiment 2 we found that this effect completely disappeared when the ordering of the first two orientations was reversed so that there was no longer a consistent path of implicit motion. Experiment 3 showed that when there is a consistent path of implicit motion the effect can still be found up to ISIs of 500 ms, although the effect weakens with longer ISIs. We interpret these results as evidence for a mental analogue to the momentum of a moving physical object.

Freyd (1983a, 1983b) has recently proposed that people's knowledge of dynamic processes may influence their mental representations of static visual stimuli. The results of one study (Freyd, 1983a) suggest that in particular, people's memory for a static visual display can be distorted according to the direction of motion or change implied by the information contained in the display. After viewing frozen-action photographs of natural visual events, subjects in her study found it harder to reject distractors that were photographs of the same event shot later in time than when they were photographs of the same event shot earlier in time. Because these photographs captured naturally evolving, or irreversible, motion, there was a possible confounding between the temporal ordering of the inspection and test displays and the plausibility of the implied physical changes.

In this report we present evidence that memory for a static visual display can also be distorted following observation of a sequence of displays that depict a reversible motion of a simple geometric form. As in Freyd's (1983a) study, we looked for a temporally dependent asymmetry in ease of rejecting distractors consisting of forward and backward displacements (a procedure that has the advantage of minimizing possible demand characteristics) and found that memory distortions fell along the direction of the implied motion. We call this effect *representational momentum* in analogy to the tendency for a physically moving object to continue along its path of motion.

Our use of a sequence of static displays to induce the effect, as opposed to using continuously moving displays, was also motivated by the desire to avoid residual perceptual aftereffects of motion. Such aftereffects would serve to diminish the strength of the predicted memory distortions, since the illusory motion would be in the direction opposite that of the actual motion of the inducting field (e.g., Beverley & Regan, 1979; Favreau, Emerson, &

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Corballis, 1972; Mayhew & Anstis, 1972). There is also evidence that motion aftereffects can bias the direction in which a static image is subsequently transformed in memory (e.g., Corballis & McLaren, 1982). Our procedure was therefore designed to minimize obvious sensory artifacts resulting from the perception of real motion.

Experiment 1

In Experiment 1 we presented subjects with three orientations of a simple rectangle with small temporal separations between presentations. These orientations can be thought of as sampled positions from an implicit path of rotation of the rectangle around its central axis. We had hoped our display would induce changes in the observer's mental representation of the rectangle, without eliciting the perception of continuous motion (or equivalently, sensations of continuous apparent motion). To the extent that we could induce such changes we expected that the representation would correspond to a rectangle that continued to rotate in the established direction. To test this we asked subjects to make a *same/different* discrimination between the third presentation and an additional, fourth, presentation that was different from the third 50% of the time. We specifically compared those cases where the fourth presentation was oriented slightly further along in the direction of implicit rotation with those cases where it was oriented slightly back toward the second presentation. We predicted that subjects would find forward cases more difficult to discriminate from the third orientation than backward cases, because the forward orientation would correspond more closely to the distorted memory of the third orientation.

Method

Subjects. The subjects were 16 Stanford undergraduates who received course credit for their participation in this study.

Apparatus and stimuli. A Megatek 5000 graphics display screen controlled by a Data General Nova computer was used to present visual stimuli. Each subject used a foot pedal and a two-key response board, which were both connected to the computer. Stimuli were very simple; there was a single central fixation point shown on the screen during intertrial intervals, and one of six basic rectangles was used during any one trial. Rectangles were always centered on the screen although orientation (as a function of angular rotation around the central axis) varied depending on the condition. The smallest rectangles subtended 7° of visual angle, and the largest, 10°.

Procedure. Subjects were tested in three blocks of 96 trials each. They were told to consider the first block to be practice. Each trial was preceded by the central fixation point. Subjects were instructed to start a trial, when they were ready and when their eyes were focused on the fixation point, by pushing down on the foot pedal. They were asked to hold their eye fixation during the complete trial and to move their eyes between trials to avoid blurring. Each trial consisted of four stimulus presentations, separated by 250-ms interstimulus intervals (ISIs). The first three orientations were presented for 250 ms and were sampled from a consistent path of rotation around the central axis of the rectangle (see top half of Figure 1). The angular distance between the first and second orientations, and the distance between the second and third orientations, was 0.3 rad (approximately 17°). For half of the subjects this rotation was always clockwise and for the other half, counterclockwise.[1] If we consider the upright rectangle as the 0-rad position, then for the counterclockwise rotation the following were the positions for the first three presentations: 0.3 rad, 0.6 rad, 0.9 rad. For the clockwise rotation the first three presentations were 1.5 rad, 1.2 rad, and 0.9 rad. Thus the third orientation was always in the same position independent of direction of rotation.

There were three types of trials, determined by the orientation of the fourth presentation. For 50% of the trials the orientation of the fourth presentation was the same as the third (i.e., at the 0.9 rad position). For 25% of the trials the fourth orientation was slightly different from the third by a 0.1-rad (approximately 6°) clockwise rotation (i.e., at the 0.8-rad position). For the other 25% of the trials the fourth orientation was different from the third by a 0.1-rad counterclockwise rotation (i.e., at the 1.0-rad position). These two types of *different* trials were used in the forward and backward conditions. The forward condition consisted of those cases where the fourth orientation was a rotation in the same direction as the first three orientations; for the backward condition, a rotation in the opposite direction. For example, for those subjects who had a clockwise rotation in the first three presentations, a forward trial was that in which the fourth presentation was also a clockwise rotation.

Subjects were instructed to watch the four presentations and then to decide, as rapidly as possible, whether the fourth presentation had the same orientation as the third. Subjects indicated their decisions by pressing one of two keys on the response board (right for *same* and left for *different*). After they pressed a key, the fourth presentation was replaced by the fixation point and they were free to initiate the next trial. Speed was stressed over accuracy. Before subjects began any trials they were told to expect 50% of the trials to be *same* trials and to look for two kinds of equally frequent *different* trials, those with clockwise and those with counterclockwise rotational displace-

[1] When we speak of *rotation* here we mean, of course, implicit rotation; subjects never actually saw a continuous rotation of the patterns.

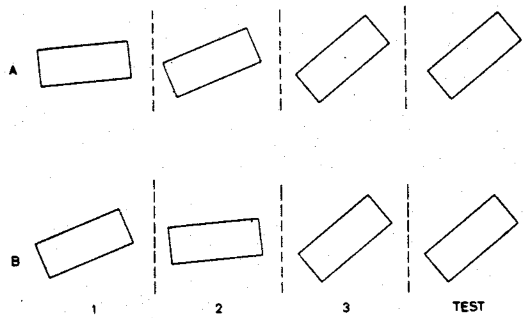

Figure 1. Examples of display sequences. (Panel A = Experiment 1 and Panel B = Experiment 2. The three stimulus presentations plus the test pattern, which were presented sequentially in the experiments, are shown here from left to right. Test patterns shown on the far right are for the *same* trials, in which the test-pattern orientation matched that of the third pattern in the sequence. Distractors consisted of identical patterns rotated 0.1 rad, approximately 6°, clockwise or counterclockwise from the third pattern.)

ments. After each subject completed the first block of 96 trials, the experimenter looked at the subject's data file, which included error rates. If the subject had very high error rates, the experimenter made a comment to that effect and encouraged the subject to slow down a bit. If the subject made more errors in the forward than the backward trials, which was almost always the case, the experimenter reminded the subject to look for both clockwise and counterclockwise displacements. In those cases where there was a very low error rate the subjects were encouraged to go more quickly. They were also reminded to hold their eye fixation throughout each trial. After this second set of instructions they went on to the second and third blocks of trials, which provided the experimental data for analysis. Within any one block of 96 trials, the subjects saw each of the six basic rectangles in 16 trials (8 same cases, 4 forward cases, and 4 backward cases). The order of the 96 trials was randomized for each block. The complete session of three blocks took about 30 min.

Results

The predicted effect was found to be strikingly robust for both reaction time and error data. Because the direction of rotation for the first three trials (clockwise or counterclockwise) made no difference for either reaction times or error rates the data were collapsed over all 16 subjects. Also, any individual reaction times greater than 2,000 ms were not used in data analysis; fewer than 1% of times were that high. The mean correct reaction time of 892 ms for rejecting distractors in the forward condition was markedly slower than that of 676 ms in the backward condition; the resulting 216-ms difference in the predicted direction was highly significant, $t(15) = 6.83$, $p < .001$. The error rate of 43.9% in the forward condition was likewise significantly greater than that of 6.4% in the backward condition, $t(15) = 6.70$, $p < .001$. Moreover each of the 16 subjects individually showed the predicted effects for both reaction time and error rate. For the *same* trials the mean reaction time was 731 ms, and the error rate was 15.8%.

Discussion

The findings of the first experiment show that following inspection of a sequence of static displays depicting the consistent rotation of a simple geometric form, distractors presented in the direction of implicit motion are much harder to reject than those presented in the opposite direction, as measured by both reaction time and error rate. We should note that although the subjects reported "knowing" that the rectangles differed in orientation and in some sense were "moving," none of them reported seeing continuous apparent motion. Also, they complained that it was very hard to tell when the fourth presentation was the same as or different from the third when the displacement was in the same direction as the implicit motion.

Experiment 2

Although the results of Experiment 1 are in the predicted direction, there remains the possibility that they could be explained in terms of some configural property of the inducing displays, independent of their temporal order. Experiment 2, designed to rule out this explanation, was almost identical to Experiment 1 except that the ordering of the first two stimulus presentations was reversed, so that the presentations no longer implicitly described a consistent path of rotation. (See bottom half of Figure 1.) There is, in fact, some reason to predict that without a consistent path of motion the effect found in Experiment 1 would be reversed. Backward trials might be more difficult than forward trials because the backward orientation is more similar to the average position, or "central tendency," of the first three presentations. Similarly, if there is any masking effect due to the first three presentations, it should interfere more with the backward orientation, which is physically closer to the earlier orientations.

Method

Subjects. The subjects were 10 Stanford undergraduates who received course credit for their participation.

Apparatus and stimuli. The apparatus and stimuli were the same as those used in Experiment 1.

Procedure. The procedure was the same as that in Experiment 1 except that the ordering of the first two orientations was reversed. Thus, for half of the subjects the first three orientations were 0.6 rad, 0.3 rad, and 0.9 rad, and for the other half the first three orientations were 1.2 rad, 1.5 rad, and 0.9 rad.

Results and Discussion

Reaction times and error rates were calculated as in Experiment 1. The mean reaction time for *same* trials was 729 ms, and the error rate was 8.1%. The mean reaction times for the forward and backward conditions (790 ms and 828 ms) did not differ significantly ($t = 1.69$, $p > .1$); the small difference of 38 ms was, in fact, in the opposite direction as that found for Experiment 1. The error rates for forward and backward conditions were 23.2% and 21.4%, respectively. Again the difference was not significant ($t < 1$). Figure 2 displays the data from both Experiments 1 and 2 for comparison.

It seems, then, that the effects found in Experiment 1 depend on the temporal characteristics of the display and not simply on some emergent configural property of the stimulus patterns. In other words, only when a consistent path of rotation is implicitly indicated is the observer's memory distorted for the final display in the sequence.

Experiment 3

Another question raised by the results of Experiment 1 is whether the effect is dependent on the relatively short ISIs. Although subjects do not report seeing continuous motion between stimulus presentations, it is still possible that the 250-ms ISI is short enough to be triggering some sort of perceptual motion detector. One thing we did to investigate this possibility was to determine at what ISI apparent motion was perceived with the display used in Experiment 1. We asked an experienced observer of apparent motion to watch the display with a sampling of ISIs, and she agreed with our observation that any ISI longer than 50 ms induced no apparent motion, and only in the cases where the ISI was less than 5 ms did the motion appear to be continuous between presentations.[2] In Experiment 3 we directly addressed the issue of the short ISI used in Experiment 1 by doubling and tripling the original interval of 250 ms. If forward cases are still more difficult to detect than backward cases at these relatively slow rates, then the effect must involve cognitive rather than sensory processes.

Method

Subjects. The subjects were 20 people, from a pool of Stanford undergraduates, employees, and summer students, who were paid for participating in the study.

Apparatus and stimuli. The apparatus and stimuli were the same as in the previous two experiments.

Procedure. The procedure used in Experiment 3 differed from Experiment 1 only regarding the ISIs, which were 500 ms for half of the subjects and 750 ms for the other half.

Results

Table 1 gives the reaction-time and error-rate results for Experiment 3. An analysis of variance revealed that the mean reaction times for the backward condition were significantly faster than those for the forward condition, $F(1, 18) = 6.42$, $p < .025$. Separate analyses were then conducted on differences between these conditions for the 500- and 750-ms intervals. For the 500-ms ISI the mean reaction time for the forward condition was significantly greater than that for the backward condition, $t(9) = 2.94$, $p < .05$. The 62-ms difference, although in the predicted direction, was only

[2] The reason such a short ISI is needed for apparent motion here presumably has to do with the long stimulus durations (250 ms) so that the total stimulus-onset asynchrony (SOA), which is sometimes argued to be the most critical temporal determinant of apparent motion (see Kolers, 1972, for a review), is at minimum 250 ms. The breakdown of apparent motion with long ISIs has been measured for the classical apparent motion paradigm, where two separate lights flickering on and off asynchronously elicit the illusion of a single continuously moving light (again see Kolers, 1972). However, we do not know of any studies using apparent rotational movement that have varied the ISI; the more common procedure is to have the ISI equal zero while instead varying the SOA (see Farrell & Shepard, 1981).

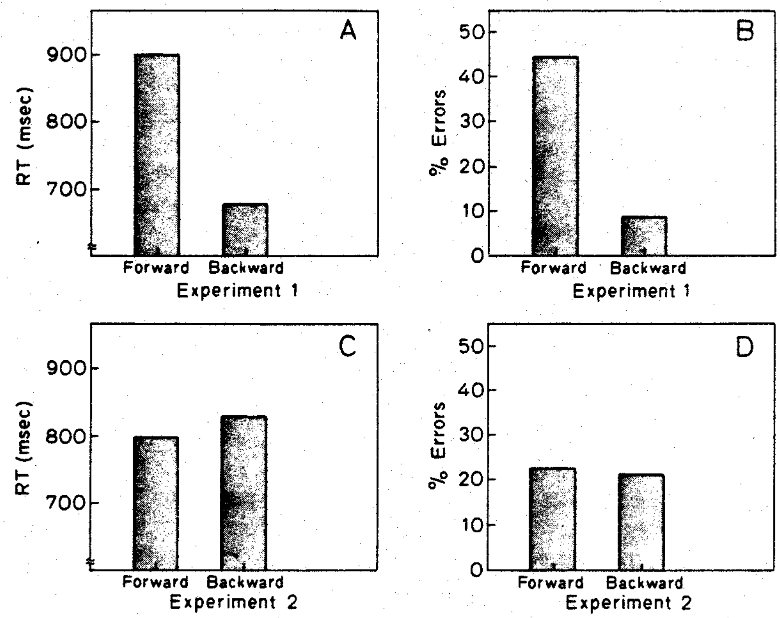

Figure 2. Mean reaction times (in milliseconds) and error rates for forward and backward conditions. (RT = reaction time; Panel A = RT for Experiment 1; Panel B = error rate for Experiment 1; Panel C = RT for Experiment 2; and Panel D = error rate for Experiment 2.)

one third of the size of the corresponding difference in Experiment 1 (where the ISI was 250 ms). For the 750-ms ISI the mean reaction time for the forward condition was not significantly different from that for the backward condition ($t < 1$), even though the small 24-ms difference was again in the predicted direction. As for Experiments 1 and 2, reaction times over 2,000 ms were eliminated, but fewer than 1% were that high.

Although only marginally significant, the overall error rate of 27.0% for the forward condition was greater than that of 16.9% for the backward condition, $F(1, 18) = 4.12$, $p < .06$. Again, this difference was in the predicted direction, as were the corresponding differences in error rate for the 500- and 750-ms ISI conditions separately. The *same* data from Experiment 3 together with the *same* data from Experiment 1 (see Table 1) suggest that the task gets easier with longer ISIs, for both reaction time and error rate decreased with increasing temporal separation.

Discussion

The results of this experiment indicate that the effect we found in Experiment 1 is still present at ISIs of at least 500 ms, although reduced in magnitude. There are several possible reasons why the size of the effect was not as great for the 500- and 750-ms ISIs as for the 250-ms ISI. One possibility is that at the longer ISIs there is a smaller implicit angular velocity. Another possibility is that subjects were not as able to hold eye fixation throughout

Table 1
Reaction Times (in Milliseconds) and Error-Rate Percentages for Three Interstimulus Interval (ISI) Conditions

ISI condition (in ms)	Trial condition: Forward	Backward	Same
250[a]			
RT	892	676	731
Error rate (%)	43.9	6.4	15.8
500[b]			
RT	744	682	678
Error rate (%)	30.6	20.5	12.0
750[b]			
RT	692	668	608
Error rate (%)	23.4	13.4	8.4

[a] Experiment 1. [b] Experiment 3.

the longer trials. Without eye fixation there is some tendency to track the rectangle, and this might have reduced the effect. An additional possibility is that some portion of the effect in Experiment 1 had, in fact, been due to triggered motion detectors, although the absence of apparent movement in that experiment would tend to rule this out. Moreover, as noted at the beginning of this article, any negative aftereffects resulting from such stimulation would be in the opposite direction from that of the obtained effects.[3]

General Discussion

When subjects were shown a sequence of static displays depicting a pattern undergoing rotation, it was much more difficult for them to reject distractor patterns that were rotated slightly ahead in the same direction as the implied motion than to reject patterns rotated in the opposite direction. This difference was completely eliminated, however, by reversing the order of the first two patterns in the sequence, so that there was no longer a consistent path of movement. When the display sequence did imply such movement, it was harder for subjects to reject the forward distractors even when the interval separating the static displays was increased to 500 ms, arguing that the effect probably has a cognitive, as opposed to sensory, basis. Since it can be described as the tendency for the memory representation of an object to change along the object's implicit path of motion, we have called the effect representational momentum.

As mentioned before, one advantage to using a distraction technique for measuring these memory distortions is that it is far less susceptible to experimental demand characteristics. In our experiments, subjects were highly motivated not to make errors, so we feel fairly confident that they were not intentionally transforming their representations along the implied paths. It is always possible, of course, that they might have mentally extrapolated the third inspection pattern to the next orientation in the orderly sequence, despite our attempts to discourage them from doing so. To address this possibility, we conducted a simple control experiment using distractors having larger angular displacements from the third pattern, such that the forward distractors were physically what would have been the next stimulus in the sequence. That is, the distractors were displaced 0.3 rad from the third orientation while all other variables were the same as in Experiment 1. We still obtained a memory distortion in the predicted direction, but the effect was much smaller and less stable than that for the smaller displacements used in Experiment 1. (The mean reaction times and error rates for the forward and backward trials were 608 ms, 6.1%, 588 ms, and 3.9%, respectively; neither the 20-ms reaction-time difference nor the 2.2% error-rate difference reached statistical significance.) Since the effect was much weaker for larger distractor displacements than for the smaller displacements used in Experiment 1, it seems unlikely that subjects were anticipating that the final inspection pattern would be the next logical orientation in the sequence.

One might ask whether a momentum effect similar to the one reported here might also occur following the mental rotation of an object (e.g., Shepard & Cooper, 1982). This may be difficult to assess using the typical mental-rotation paradigm, since an overshoot of the mentally rotated image would simply add a constant value to all reaction times (for, evidently, mental rotations are performed at constant rates of speed, independent of the extent of the rotation; see Cooper & Podgorny, 1976; Shepard & Metzler, 1971). Interestingly, however, Foster and Gravano (1982) have recently demonstrated an observable overshoot in visual apparent movement created between a curved and straight line. Their subjects reported that the straight line appeared to bend back slightly in the direction of apparent motion, displaying the opposite curvature, as if a semirigid bar were stretched and then released.

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[3] A further possibility is that tilt aftereffect, induced by the inspection patterns, might have contributed to the momentum effect at the shorter intervals. Such aftereffects could, conceivably, make the test patterns appear rotated in the direction of implicit movement and would decay over time (e.g., Campbell & Maffei, 1971; Gibson & Radner, 1937). However, any interference resulting from tilt aftereffects would be larger for the backward distractors than the forward distractors, since the former would appear to be shifted toward the third pattern orientation, whereas the latter would appear to be shifted away from it.

Although our primary concern in the present study was to demonstrate the momentum effect, it would be important in future studies to determine the range of stimulus conditions that reliably alter the effect. For example, we plan to vary the number of inducing displays, as well as their temporal spacing, to see how this influences the strength of the effect. In addition, we plan to measure how rapidly the effect decays by varying systematically the size of the distractor displacements together with their delay. It would also be interesting to know the extent to which people can compensate for the effect if they know about it in advance. Our hope is that as we begin to learn more about the effects of various stimulus parameters and task instructions on the obtained memory distortions, we will be able to develop a fuller theoretical account of representational momentum.

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