Memory & Cognition
1993, 21 (4), 449-457

Memory for position and dynamic representations

MARCO BERTAMINI
University of Virginia, Charlottesville, Virginia

Memory for the position of an object is biased. When asked to judge whether an object has changed its position with respect to a position shown a few milliseconds before, observers tend to detect the displacement more often when the displacement is not in the expected direction (downward for a falling object). The hypothesis proposed by Freyd (1983, 1987) states that the internal representation of an object is intrinsically dynamic. Therefore, the forces perceived as acting on the object affect the representation. Quantitative predictions of this model were tested in three experiments by measuring memory distortion for the position of an object on an inclined plane. Angle of inclination and retention interval were varied. The results for different inclinations support the physical model. The time course of the memory distortion suggests a new view about the relation between this phenomenon and very short-term memory.

Using static displays such as photographs or drawings, Freyd (1983; Freyd, Pantzer, & Cheng, 1988) found that short-term memory for the position of objects shows a systematic error in the direction in which objects should move when the display is interpreted as part of a dynamic event. For example, Freyd (1983) showed a photograph of a person jumping off a wall and then a photograph of the same event shot a few milliseconds later or earlier. Observers took longer to correctly say that the photographs were different when the pair were in real-world temporal sequence—that is, when the second photograph had been taken after the first—than when they were in reverse order. Freyd et al. (1988) used drawings of simple objects. When asked to remember the position of a falling flower vase, observers tested by means of a probe flower vase showed a preference for a position shifted down. That is, the remembered position of the object was shifted in the direction of gravity.

Freyd (1987) suggested that even when observers are presented with purely static displays, they appreciate the dynamic information conveyed by the particular relations among objects. The resulting memorial representation is always dynamic and, within this representation, forces act on the position of the object. The same rules governing a physical event—the laws of classical mechanics—are used to describe representational changes over time. Thus, this model of inner representation is called a physical model. In the context of the physical model of representation, it has also been found that memory for the position of a moving object that suddenly disappears is distorted in the direction of motion, as if the represented object continues along its path of motion after the vanishing of the stimulus. The typical experiment consists in presenting an object in an implied translation or rotation; memory is then tested by means of a probe object presented after a very short retention interval (Freyd & Finke, 1984). This has been seen as evidence for a correspondence between the physical law of conservation of linear momentum and the characteristics of the representation. Freyd and Finke named this phenomenon *representational momentum*. Representational momentum has the following characteristics: (1) The effect depends on the implied motion speed; moreover, it depends more on the final acceleration than on the mean speed; (2) the effect increases as the retention interval increases (at least for the first 300 msec); and (3) the effect is not due to low-level systems of motion detection, because its direction is opposite to the well-known aftereffect of motion and because the effect is strongly affected by the similarity between the object and the probe object (Freyd, 1987; Kelly & Freyd, 1987).

As for the use of a system of laws borrowed from physical mechanics to describe the inner representation, a strong and a weak view can be distinguished: (1) The strong view is that the physical model embodies all the most important features of the inner representation, because physical laws have been internalized during the evolution of the cognitive system; (2) the weak view suggests that representation is in some specific way constrained by ecological factors (physical laws important in the human environment).

Another more controversial point is the modularity of the effect. The notion of modularity is related to the idea that the characteristics of the stimulus determine the effect in a direct way. Kelly and Freyd (1987) argued that representational momentum appears to be informationally

This research was supported by Air Force Office of Scientific Research Grant AFOSR-91-0057 and NASA Grant NCA2-468 to Dennis Proffitt. I thank Jennifer Freyd, Michael Ranney, and Géry d'Ydewalle for their reviews, Dennis Proffitt and Frank Durgin for comments on the manuscript, and Steve Jacquot for his assistance with the software.
Address correspondence to M. Bertamini, Department of Psychology, Gilmer Hall, University of Virginia, Charlottesville, VA 22903-2477.

encapsulated, or *modular*, because it is very rapid, impervious to practice or error feedback, and not influenced by beliefs. These are Fodor's criteria for defining a modular system (Fodor, 1983). In this sense, representational momentum tasks are different from other memory tasks, which are affected by subject's expectations (Freyd, 1987). This modularity of representational momentum may also be a characteristic of the memory distortions for static displays; however, this has not been investigated.

Recent experiments pose a serious problem for the analogy between mental and physical processes. Verfaillie and d'Ydewalle (1991) studied representational momentum by using implied periodical events such as a back-and-forth motion or a motion along a sinusoidal path. The result of these experiments is that the extrapolation of the object's motion beyond its final position occurs on the basis of the higher level structure of the motion event. The largest memory distortion was found when the visual system was made to expect a sudden increase in velocity, whereas the memory shift size dropped when the visual system was made to expect a direction change (Verfaillie & d'Ydewalle, 1991). The memory distortion is in this case affected by expectations, and these expectations are in a direction different from the direction dictated by the mechanics of the event. The best example of this is the case in which the position of an object moving along a sinusoidal path is in fact remembered along this path, even if the linear momentum of the object is tangential to the curve. Verfaillie and d'Ydewalle conclude that the anticipated immediate future position of the object affects the representation, and the anticipation of the immediate future is different from a simple momentum of representation. This finding is in agreement with another recent finding obtained by Freyd and Taylor (1990). Using an object traveling in a curved tube, they found that the memory distortion at the end of the tube was not on the direction tangential to the curved path, but was along the curved path. The tangential path is the one accurately predicted by classical mechanics. The curved path is instead consistent with the medieval impetus theory about trajectories of projectiles, and also with the judgments of many naive observers (Kaiser, McCloskey, & Proffitt, 1986; McCloskey, Caramazza, & Green, 1980). The impetus is a motion impressed on a body that tends to continue once started, so that a linear as well as a curvilinear motion is believed to continue in absence of external forces. The results obtained by Freyd and Taylor (1990) and by Verfaillie and d'Ydewalle (1991) show that the memory distortion is in the direction of the anticipated future position of the object.

A possible conclusion is that memory distortions are the consequence of representational momentum, but the evolution of these representations is characterized by laws different from the laws of classical mechanics. This paper is a quantitative assessment of the characteristics of the memory distortion, and the fit of the physical model, in the case of an object on an inclined plane.

EXPERIMENT 1

Experiments with static displays, in which motion is suggested only by the action of forces like gravitation, are very important for one who wishes to assess the validity of the analogy between physical and representational characteristics. Both figural and kinematic parameters affect representational momentum, whereas in the case of static displays there are only figural parameters, and it is possible to analyze them thoroughly.

Ranney (1989) criticized the modularity of the memory distortion and the physical model. In particular, he pointed out that the physical displacement of a free-falling object would be much greater than the slight memory distortion actually found. The memory distortion is small, and its size may be affected by methodological details, yet the physical model ought not to be abandoned because of a difference in size. The relevance of represented forces in producing the distortions may be ascertained by varying those forces. For the physical model to be useful, the memory distortion is expected to show a function consistent with physical laws. A way to study the problem of predictive power of the physical model is to do what Galileo did to study gravitation: change systematically the system of forces by means of an inclined plane. This is the rationale behind the first experiment. Another point in Ranney's commentary was that we need more data on the time course of the effect. In the present experiment, the retention interval was therefore varied.

One of the interesting although problematic features of representational momentum is its function for the length of the retention interval (Freyd & Johnson, 1987). The effect increases monotonically up to 300 msec and then decreases before reaching a plateau. The decrement after 300 msec cannot be explained by the physical model. In Freyd and Johnson's experiments, during an induction phase an object was shown in a series of positions at different orientations. The memory for the last position was then tested with a probe object. To explain the decrement for longer retention intervals, Freyd and Johnson suggested that there could be a memory averaging process, so that what is remembered is the average position of the series of different positions of the object. This memory averaging process could be a separate and distinct process taking place only with long retention intervals, and it may change the shape of the function for the memory distortion.

In the case of static displays, the physical model predicts an increase of the effect with the retention interval, but the memory distortion cannot increase forever. A plateau should be reached; it would indicate the maximum memory distortion obtainable. However, unlike in Freyd and Johnson's (1987) experiments, there is no possible memory averaging process because the object is not presented in a series of different positions, so that there is no reason to predict a decrement before reaching a plateau.

A physical model of the representation implies that the physical equations regarding dynamic events have equivalent equations regarding memory processes. In the case of an inclined plane where an object is rolling without friction, the following equation gives the distance traveled by the object:

$$d = v_0 t + \frac{1}{2} g \sin \alpha \, t^2, \quad (1)$$

where d is distance, v_0 is the velocity at time 0, t is time, g is the gravitational constant, and α is the angle by which the plane is inclined. If we assume that the object has just started rolling, the first term can be deleted. Given that everything else is a constant, time (t^2) and inclination ($\sin \alpha$) are the only two variables affecting d. From Equation 1 the predictions for the first experiment are as follows: (1) a linear effect of the sine of the angle of inclination, (2) a linear effect of the square of the retention interval, until a plateau is reached, (3) a linear interaction of these two variables (a linear fan in the graph of these variables).

For the reasons discussed above, the results of this experiment will be compared with the corresponding results obtained for representational momentum, but it is important to keep in mind the differences in the task and in the predictions. There is no assessment of the time course of the memory distortion for static displays in the literature against which to directly compare the outcome of this experiment.

Method

Subjects. Twenty-four subjects participated (12 males and 12 females). They were undergraduate students at the University of Virginia and were fulfilling a requirement of an introductory psychology course. All subjects had normal or corrected-to-normal vision. They were naive with respect to the hypotheses of the experiment until after their data had been collected.

Display. The displays simulated a gray inclined plane on a white background, as shown in Figure 1. The direction of the slope was varied between subjects (/ and \ ). The size of the display was 21×21 cm, with an inclined plane of 16 cm. On this plane, a black circle (16 mm in diameter) was drawn, either one radius from the middle of the slope toward the top, or one radius toward the bottom. This scene was presented for 1.2 sec; then the black circle was removed and it reappeared after a variable retention interval. This second scene was displayed until a response was made by the subject.

Apparatus. Displays were computed and shown on a Sun 3/60 workstation equipped with a high-resolution graphics monitor. The monitor has a refresh rate of 60 Hz, and a resolution of 1,152×900 pixels. The system clock can be read from software with an error lower than 1 msec.

Design and Procedure. Four displays were examined, in which the plane was inclined at 15°, 30°, 45°, or 60°. The six retention intervals spanned from 100 to 600 msec in 100-msec steps. The displacement of the black circle with respect to the initial position was 2/6, 1/6, or 0 radii. When there was a displacement, half of the times it was in one direction (upward on the slope), and half of the times in the other direction (downward on the slope), yielding five possible displacements: −2/6, −1/6, 0, 1/6, and 2/6 radii (negative values indicate the upward direction). The subjects were asked to sit at a comfortable distance from the screen (about 50 cm) and keep this distance constant during the experiment. The subjects had to choose among three possible responses: (1) perception of a displacement toward the top of the slope (coded −1); (2) perception of no displacement (coded 0); (3) perception of a displacement toward the bottom of the slope (coded 1). The response was entered by the subject by means of three contiguous keys of the keyboard. Given that only three keys were used, the subject had

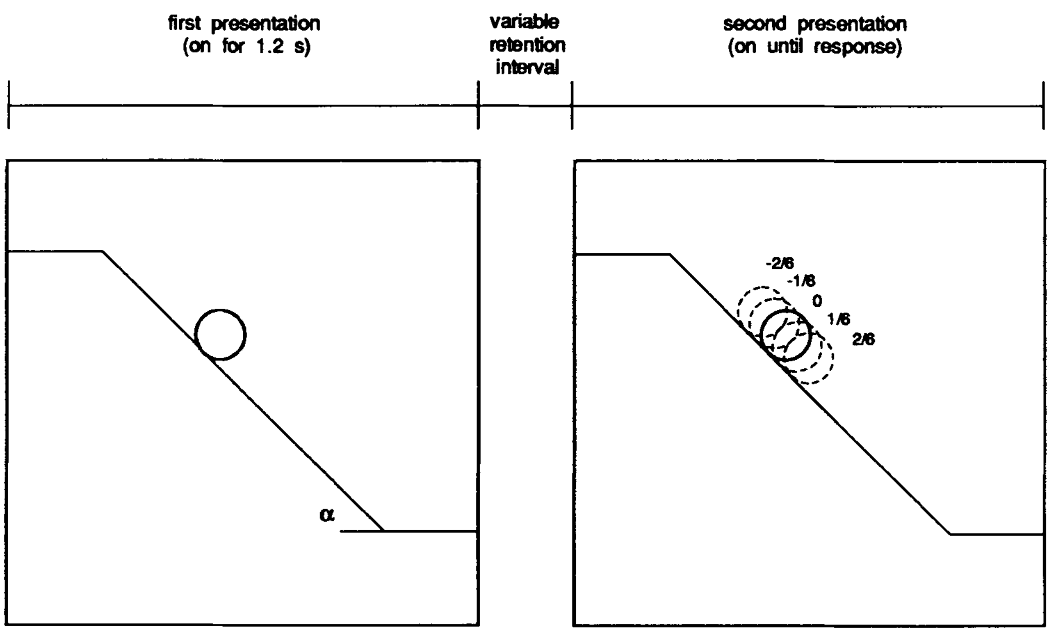

Figure 1. Description of the display used in Experiments 1 and 3. The angle α measures the inclination of the plane. The circle shown on the slope in the first frame disappeared during the retention interval. A probe circle reappeared in the second frame in one of five different positions. The numbers indicate the displacement in radii for each position.

no need to look at the keyboard. Twelve subjects (6 males and 6 females) saw the first type of slope (/), and 12 (6 males and 6 females) saw the second type of slope (\ ). The subjects had a short practice period (10 trials), the results of which were not stored, and then they saw two blocks of stimuli. Each block consisted of 240 trials (6 retention intervals × 5 different displacements × 4 inclinations × 2 positions of the circle on the slope). The instructions were written on a sheet of paper, and the experimenter asked each subject about them, to be sure that the task was clearly understood. Accuracy as well as speed were stressed.

Data analysis. The data analysis consisted of four steps.

1. To verify the presence of the memory distortion, the proportion of no-displacement responses was analyzed for the five different displacements of the object (−2/6, −1/6, 0, 1/6, 2/6 radii). This distribution is unimodal and roughly symmetrical. For each subject separately, and for each level of inclination, the data were subjected to a quadratic regression. The location of the peak of the curve was taken as an estimation of the memory shift (for a similar analysis, see Finke & Shyi, 1988). In other words, this value is an estimate of how much the object should be displaced to make the no-displacement response most likely (point of subjective rest). According to the hypotheses of this experiment, it was expected that a positive shift would result for every level of inclination.

2. The subjects had a choice of three different responses: no displacement, displacement down the slope, and displacement up the slope. Therefore, the use of the proportion of no-displacement responses implies throwing away part of the information. To give a description of the proportion of times that each response (perception of a displacement upward, no displacement, and downward) was chosen by the subjects, four histograms are presented in Figure 2. Each histogram is relative to a different inclination of the slope, and it describes the proportion of responses given. All the other variables are collapsed together.

A new dependent variable was computed by averaging the responses to the five different displacements. This implies that five observations were pooled together in only one observation. This value is a quantitative measure of a directional bias. To obtain a measure of memory distortion, the sign of the values was reversed because a bias to detect upward displacement corresponds to a downward distortion in memory for position. An *ideal* observer would have a score of zero for every condition; an observer whose responses were completely random would tend to have a score of zero for every condition. According to the hypotheses, it was expected that a positive distortion would result for every condition. This measure of memory distortion was used in the analyses described in (3) and (4).

3. An analysis of variance (ANOVA) was performed to test the effect of type of slope and gender (between-subject variables), and the effect of position of the circle with respect to the middle of the slope (within-subject variables). Thus the model was a 2×2×2 factorial design.

4. A regression analysis was performed to test the effects of the variables retention interval and inclination [sin(angle)] and their interaction. A multivariate approach for the repeated measures variables was adopted.

Results

1. Among the 24 subjects, the quadratic fit accounted for 47%-99% of the variance. The minimum memory shift was −0.509, and the maximum was 0.700 sixths of a radius (0.679 and 0.933 mm). For the 15°, 30°, and 45° of inclination, the average memory shifts of the 24 subjects were, respectively, 0.004 (SD = 0.219), 0.064 (SD = 0.169), and 0.017 (SD = 0.218) sixths of a radius. These values are positive as was expected, but a t test showed that none of these means were significantly different from zero. For the 60° of inclination, however, the average memory shift of the 24 subjects was 0.116

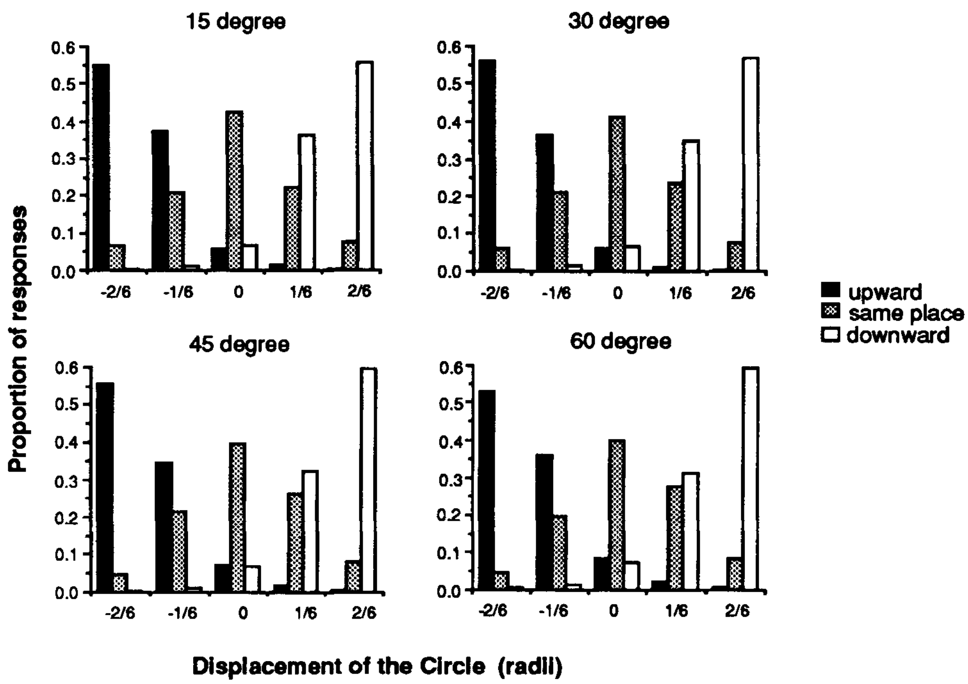

Figure 2. Data from Experiment 1. Proportion of responses given for each displacement of the object on the slope.

sixths of a radius ($SD = 0.123$). This value is statistically different from zero [$t(23) = 4.617, p < .01$]. Therefore the point of subjective rest is displaced downward, but only for the steepest slope.

2. The means of the dependent variable for the four different inclinations were, respectively, 0.012 ($SD = 0.094$), 0.015 ($SD = 0.093$), 0.045 ($SD = 0.082$), and 0.058 ($SD = 0.075$). The four values were positive, as was expected, but the values for the inclinations of 15° and 30° were not significantly different from zero. The values for the two steepest inclinations, however, were significantly different from zero [$t(23) = 2.713, p < .05$, and $t(23) = 3.808, p < .01$]. Thus, for a plane of 45° or 60° of inclination, a displacement of the object toward the top of the slope was more often detected than the reverse, or cases in which the object did not move were judged as a displacement toward the top of the slope. These two cases can both be interpreted as being due to the same memory distortion.

3. The effect of the variable type of slope was significant [$F(1,20) = 6.189, p < .05$]. The average for the slope leaning to the right (\ ) was 0.0648, and the mean for the slope leaning to the left (/) was 0.0009. These values show a left-to-right difference in perception of displacement. Gender was not significant [$F(1,20) < 1$]. Position with respect to the middle of the slope was significant [$F(1,20) = 6.096, p < .05$]. This difference implies that the memory distortion was slightly larger when the object was shown at the lower position. None of the first-order interactions were significant.

4. A graph with the average memory distortion for the variable retention interval is shown in Figure 3A. A graph with the average memory distortion for the variable inclination is shown in Figure 3B. A linear combination of the score at different levels of retention intervals was used to test the effect of time. No significant linear or quadratic effect was found [$F(1,23) < 1$; $F(1,23) < 1$]. A significant cubic trend was found [$F(1,23) = 12.92, p < .01$]. A new combination was used to test the effect of time for the first three values (100, 200, and 300 msec) of retention interval. This was done because the graph of Figure 3A suggests that the effect is present only for short retention intervals. The linear trend of the new combination was significantly different from zero [$F(1,23) = 5.87, p < .05$]. An analysis similar to the analysis of retention interval was performed for the inclination of the plane. A linear effect was found for the inclination of the plane [sin(angle)] [$F(1,23) = 4.59, p < .05$]. As for the interaction between retention interval and inclination, a new combination was computed from the combinations analyzed previously. Figure 4 displays the average score for retention interval for different inclinations. The new combination tests the linear interaction of these two variables (linear fan). This linear interaction was not significant [$F(1,23) = 1.24$]. A linear effect of retention interval was present only within 300 msec; therefore, the same test was performed only with retention intervals of 100, 200, and 300 msec. This linear interaction was significant [$F(1,23) = 4.52, p < .05$]. None of the higher order polynomials gave significant interactions. In agreement with the fact that the effect is clearly present only for the steepest inclination, Figure 4 shows that there is a clear increment in the slope for retention interval only when we move from 45° to 60° of inclination. It is difficult to see any trend after 300 msec.

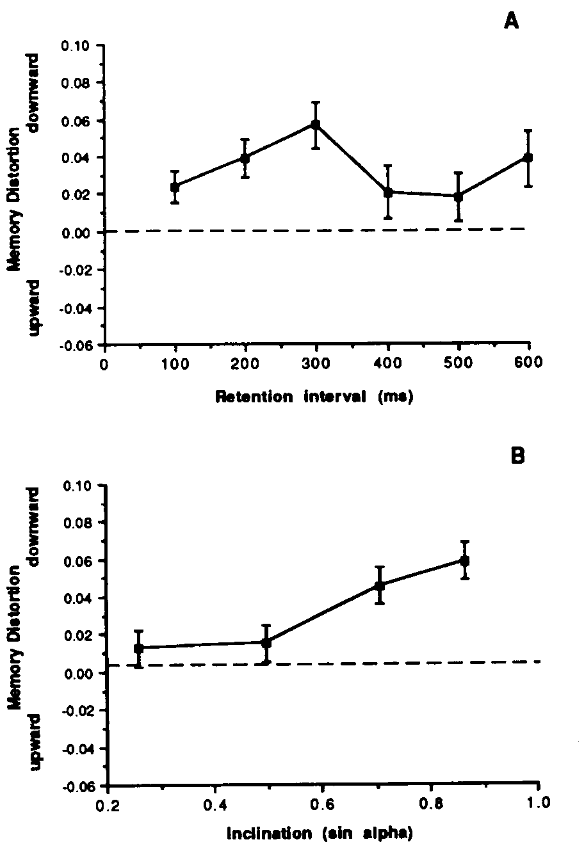

Figure 3. Data from Experiment 1. (A) Memory distortion as a function of retention interval. (B) Memory distortion as a function of the inclination of the plane. The sine of the angle has been used on the abscissa to facilitate the identification of a linear increment of memory distortion as a function of the sine of the angle.

Discussion

The goal of this experiment was to access the predictive power of the physical model for these kinds of memory tasks. For this reason, polynomial effects of retention interval and inclination were tested, and also the polynomial interaction of these two variables was tested.

The pattern of results is consistent with the predictions of the model only in an approximate way (see Figures 3 and 4). One out of three predictions based on the physical model was statistically significant, namely the effect of inclination. There may be a problem of power, because the effect size is small. It is very important, however, to consider the linear increment of the memory distortion within a range of 300 msec (see Figure 3A). In this range, both retention interval and inclination have a linear ef-

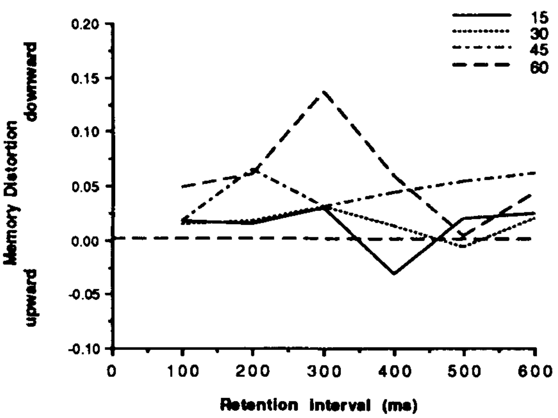

Figure 4. Data from Experiment 1. Memory distortion as a function of retention interval and for different Inclinations.

fect, and their linear interaction is also significant. For longer intervals, a plateau was found, and this cannot be explained in terms of a ceiling effect, because the memory distortion was much smaller than the smallest displacement of the circle on the slope. This plateau may be the maximum size of the memory distortion. The decrement after 300 msec, however, even if in agreement with the time course of representational momentum (Freyd & Johnson, 1987), is difficult to explain.

An effect of the position of the object on the slope was found. The memory distortion was larger when the object was in the lower position. This can be explained if we do not ignore the first term in Equation 1. If the object is perceived by the subject as rolling down the slope, the first term is larger for the lower position of the circle. As for the left-to-right difference, this effect was tested more directly with the next experiment.

EXPERIMENT 2

The first experiment showed a difference effect for the two types of ramps (/ and \ ). This asymmetry may be the consequence of a difference between the memory for displacements to the left versus memory for displacements to the right. The second experiment was devised to test this hypothesis. The display was identical to the one used in the first experiment, but the circle was on a flat surface.

Method

Subjects. Twelve subjects participated (6 males and 6 females). They were undergraduate students at the University of Virginia and were fulfilling a requirement of an introductory psychology course. All had normal or corrected-to-normal vision. They were naive with respect to the hypotheses of the experiment until after their data had been collected.

Apparatus and Design. The apparatus was the same used in Experiment 1, except that instead of a ramp a flat line was used. Two positions of the object on the line were used, one radius to the left and one radius to the right of the center of the display. Five displacements of the circle were used, as in Experiment 1: −2/6, −1/6, 0, 1/6, and 2/6 of the radius. In this case, negative values were used to indicate a displacement to the left. After a short practice, the subjects saw two blocks of stimuli. Each block contained 60 trials (6 retention intervals × 5 different displacements × 2 positions of the circle on the line). The subjects had to choose among three possible responses: (1) perception of a displacement toward the left (coded −1); (2) perception of no displacement (coded 0); (3) perception of a displacement toward the right (coded 1).

Results and Discussion

A histogram with the distribution of the proportion of no-displacement responses for the five different displacements of the object (−2/6, −1/6, 0, 1/6, 2/6 radii) is shown in Figure 5A. This distribution is unimodal and roughly symmetrical. For each subject separately, the data were submitted to a quadratic regression. The location of the peak of the curve was taken as an estimation of the memory shift. The quadratic fit accounted for 46%-87% of the variance. The memory shifts for all but 1 of the 12 subjects were positive.

As described in the data analysis section of Experiment 1, the average of the response to the five displacements of the probe circle was computed, and its sign was changed. With the use of this new dependent variable—which is a measure of memory distortion—a positive mean was found for all but 1 of the 12 subjects. It is important to remember that in this experiment, a positive distortion is a distortion to the right, whereas in the first experiment, it was a distortion downward. The mean distortion

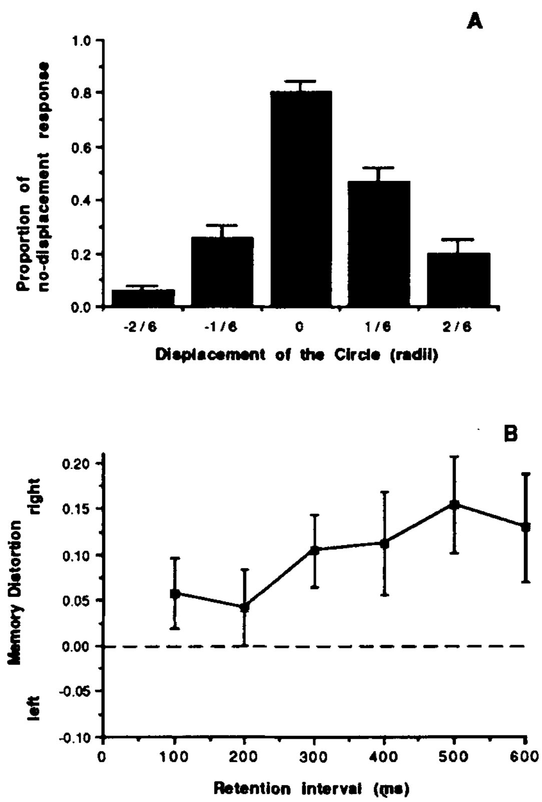

Figure 5. Data from Experiment 2. (A) Proportion of no-displacement response as a function of displacement of the object along the line. (B) Memory distortion as a function of retention interval.

was 0.1 (SD = 0.141), significantly different from 0 [$t(11) = 2.463, p < .05$]. The function of memory distortion for retention intervals is presented in Figure 5B. An ANOVA was performed to test the variables gender and retention interval. A significant effect of gender was found [$F(1,10) = 5.01, p < .05$], but there was no effect of retention interval and no interaction gender × retention interval [$F(5,50) = 2.25$; $F(5,50) = 1.777$].

A tendency to use the index finger more often than the annular finger would explain these results. However, 3 of the 12 subjects were left-handed, and all 3 showed the same bias despite the fact that the left hand was used to enter the responses. The mean memory distortion for the 3 left-handed subjects was 0.1, which is exactly the same as the average memory distortion for the right-handed subjects. Thus, the conclusion of this experiment is that displacements to the left were detected more often than displacements to the right.[1] This bias does not affect the interpretation of the results of the first experiment, given that the memory distortion found was the net effect after balancing left and right ramps. On the other hand, this left-to-right bias is a new aspect of the problem. This bias may be explained as a consequence of reading attitudes typical of our culture. If so, such a memory distortion appears to be permeable to factors different from the dynamic aspects of the event. A similar finding and a related discussion have recently been put forward by Halpern and Kelly (1991).

EXPERIMENT 3

The first experiment showed that a linear effect of time is present only for very short retention intervals, below 300 msec. The memory distortion was still present for a 600-msec interval, and it does not appear to decrease for longer retention intervals. To test the hypothesis of a limit in the interval duration after which the distortion is not present anymore, a third experiment was run. It was identical to the first, but longer retention intervals were used—up to 1 sec.

Method

Subjects. Sixteen subjects participated (8 males and 8 females). They were undergraduate students at the University of Virginia and were fulfilling a requirement of an Introductory Psychology course. All had normal or corrected-to-normal vision. They were naive to the hypotheses of the experiment until after their data had been collected.

Apparatus and Design. The displays and the apparatus were those used in Experiment 1. The design was also the same, except for the choice of the retention intervals. The six retention intervals spanned from 500 to 1,000 msec in 100-msec steps. Eight subjects (4 males and 4 females) saw the first type of slope (/), and 8 (4 males and 4 females) saw the second type of slope (\ ). After the practice trials, the subjects saw two blocks of stimuli. Each block was 240 displays long (6 retention intervals × 5 different displacements × 4 inclinations × 2 positions of the circle on the slope).

Data analysis. The data analysis consisted of three steps.

1. A measure of memory distortion was computed by taking the average of the responses of the subject for the five different displacements, and changing its sign. This dependent variable is discussed in the data analysis section of Experiment 1.

2. An ANOVA was performed to test the effects of type of slope and gender (between-subject variables), and position (within-subject variable).

3. A regression analysis was performed to test the effects of the variables retention interval and inclination [sin(angle)] and their interaction. A multivariate approach for the repeated measures variables was adopted.

Results

1. The means of the dependent variable for the four different inclinations were, respectively, −0.023 (SD = 0.147), 0.014 (SD = 0.110), 0.043 (SD = 0.104), and 0.084 (SD = 0.103). The values for the inclinations of 15°, 30°, and 45° were not significantly different from zero. The value for the steepest inclination, however, was significantly different from zero [$t(15) = 3.258, p < .01$]. This negative value implies that there is a memory distortion for the steepest slope.

2. The effect of the variable type of slope was significant [$F(1,15) = 21.64, p < .01$] and it shows the same left-to-right difference observed in Experiment 1. The mean for the slope leaning to the right (\ ) was 0.101, and the mean for the slope leaning to the left (/) was −0.0419. Gender was not significant [$F(1,15) = 2.05$].

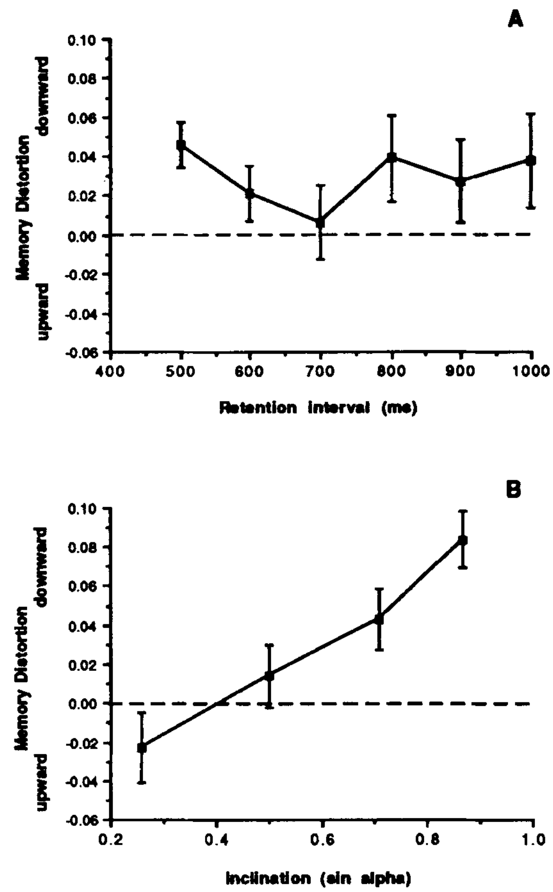

Figure 6. Data from Experiment 3. (A) Memory distortion as a function of retention interval. (B) Memory distortion as a function of the inclination of the plane. The sine of the angle has been used on the abscissa to facilitate the identification of a linear increment of memory distortion as a function of the sine of the angle.

Position was not significant [$F(1,15) = 3.68$]. None of the first-order interactions were significant.

3. A graph with the average score for the variable retention interval is shown in Figure 6A. A graph with the average score for the variable inclination is shown in Figure 6B. Combinations of the score at different levels of retention intervals (in milliseconds) were used to test different trends of retention interval. No significant linear or quadratic effect was found [$F(1,15) < 1$; $F(1,15) = 1.69$]. An analysis similar to the analysis of retention interval was performed for the inclination of the plane. As in Experiment 1, a significant linear effect was found for the inclination [sin(angle)] [$F(1,15) = 11.51, p < .01$]. As for the interaction of retention interval and inclination, new linear combinations were computed; they did not show any linear or quadratic significant interactions.

Discussion

The pattern of results is consistent with the result from the first experiment. Only one of the three predictions based on the physical model was statistically significant—namely, the effect of inclination. The memory distortion was still present for retention interval as long as 1 sec, and there was no evidence of a decrement for longer intervals. This is in agreement with the prediction of a plateau.

The effect of position of the circle on the slope found with the first experiment was not replicated with the third. The effect of the type of slope, however, was still present.

GENERAL DISCUSSION

These experiments were conceived as a quantitative test of a formal model. In general, the model turned out to have poor predictive power, because the three predictions as a whole were not met in Experiment 1 or in Experiment 3. It is implicit in a physical model of representation that physical laws have been internalized by the representational system. There are reasons to believe that this internalization—if present—is not perfect, and that the parallel between physical laws and representational laws ought to be considered as being mostly metaphorical. For example, the experiments by Verfaillie and d'Ydewalle (1991) and Freyd and Taylor (1990), described in the first part of this paper, point in such a direction. The momentum of the representation is a continuation of the pattern of motion presented. With respect to the distinction between a strong and a weak formulation of the physical model of inner representation, it is clear that the strong position is difficult to defend.

Within short retention intervals, the physical model is a good model. The only problem is that the effect of time seems to be linear rather than exponential. There are too few data points in this range to draw any final conclusion, but a linear effect of time does not necessarily point against the usefulness of a physical model. In real mechanical events, such as the falling of an object or the rolling of a ball, the function is exponential only if we ignore drag. Given that drag increases with speed, many functions are possible. For example, a constant velocity is a possible event.

The novel finding from the present study is that the temporal function of memory distortion is not explained by any theory of memory representation. If a basic representation exists on which all memory tasks rely, then memory distortions should show some kind of monotonic function over time. The idea of representational momentum, in particular, predicts an increase at the beginning followed by a flattening of the effect. On the other hand, the empirical function as shown in Figure 3A appears to have two components. There is a monotonic increase for the first 300 msec, then there is a rapid decrease, and then there may be a slight increase again or a plateau. If there is a limit after which memory is not distorted, this limit should be found for intervals longer than 1 sec, as implied by Figure 6A.

In trying to find an explanation for the time course of this memory distortion, a first important point is the fact that apparent motion is present for intervals shorter than 300 msec (Neuhaus, 1930). It is known that motion detection is more sensitive than spatial discrimination. Surprisingly, detection of motion does not appear to be helpful in avoiding memory distortions; in fact, the largest distortion is present for a retention interval of 300 msec. It is true, however, that the idea of a basic representation for every kind of memory task is not adequate to describe experimental evidence. A different and special kind of memory is present for the first short period of time. What was first described as an iconic memory (Sperling, 1960, 1963) has been revised and is no longer considered to be a pure iconic storage, in the sense of a visible persistence of the image (Coltheart, 1980; Di Lollo, 1980; Irwin & Yeomans, 1986). The duration of this very short-term memory is 150-300 msec. The information stored is assumed to contain spatial coordinates, but as time passes, neighboring stimuli are more likely to be confused with target stimuli (Irwin & Yeomans, 1986). In other words, identity information is retained better than information about position.

Although the present experiments do not adequately study short-term visual memory, in that no masking of the stimulus was used, a speculation on the role of a very short-term memory is possible. This visual storage is based on something more than a visible persistence, but is basically an analogue storage, in the sense that a spatial representation of the scene is present. If this analogue representation has internalized physical laws, this may explain why predictions from the physical model of representation are met for retention intervals no longer than 300 msec. In fact, within this range, there is a linear effect of inclination, a linear effect of retention interval, and a linear interaction between these two variables.

To summarize, three points can be made: (1) the effect of type of slope (/ vs. \ ) is evident. The explanation is probably a left-to-right bias due to reading experience. Displacements to the left are detected more often than displacements to the right. (2) The memory distortion did not increase linearly with retention interval. The effect was present and increased linearly when the retention interval was shorter than 300 msec, after which it dropped to a smaller level. In this range, retention interval and inclination show a linear interaction. This finding is consistent with Freyd and Johnson's (1987) study on the time course of representational momentum. It is important to note that, unlike representational momentum, this result cannot be explained in terms of a memory averaging process, because only static displays were used in these experiments. (3) The last point concerns the validity of the physical model of inner representation. As for the effect of the inclination of the plane, the prediction of a linear increment was confirmed in both the first and the third experiments. In other words, the laws governing people's memory distortion are consistent with the physical laws of motion. Nevertheless, a memory task of this sort is characterized by a small effect size. This can be a consequence of the difficulty in isolating other processes present in this kind of task, but this fact in itself suggests that the phenomenon is not modular—that is, impermeable to other cognitive processes. As for the effect of retention interval, the time course of the memory distortion suggests that different processes take place within different ranges of retention interval. Although more quantitative research on this point is necessary for one to discover the nature of these different processes, a speculation about the role of short-term visual memory has been attempted in the General Discussion section. The results of the present research can be summarized by saying that memory distortion for position follows laws similar to the physical laws of motion—that is, the laws of classical mechanics—for only short retention intervals (below 300 msec). The distortion is still present for intervals much longer than 300 msec, but it shows a quite different behavior.

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NOTE

1. In the context of representational momentum, Hubbard and Bharucha (1988) studied misjudgment of the vanishing point for linear motion. The error was in the direction of motion, and it was larger for motion to the left than for motion to the right. This asymmetry was task specific, because when a forced-choice response was used, the effect was not replicated. Hubbard and Bharucha's observation is in the direction opposite to the finding reported here. However, the findings are not comparable, because in their paradigm (linear moving elements) eyetracking probably had a very important role.

(Manuscript received April 13, 1992;
revision accepted for publication November 6, 1992.)