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Andrea R. Halpern and Michael H. Kelly

People remember moving objects as having moved farther along in their path of motion than is actually the case; this is known as representational momentum (RM). Some authors have argued that RM is an internalization of environmental properties such as physical momentum and gravity. Five experiments demonstrated that a similar memory bias could not have been learned from the environment. For right-handed S, objects apparently moving to the right engendered a larger memory bias in the direction of motion than did those moving to the left. This effect, clearly not derived from real-world lateral asymmetries, was relatively insensitive to changes in apparent velocity and the type of object used, and it may be confined to objects in the left half of visual space. The left–right effect may be an intrinsic property of the visual operating system, which may in turn have affected certain cultural conventions of left and right in art and other domains.

The major function of perceptual systems is to construct a useful representation of an organism's environment and its relation to that environment. In extensive research in perception, investigators have therefore tried to specify the structure of these representations and the principles used to build them. One heuristic for identifying these principles focuses on ubiquitous aspects of the environment. Certain characteristics of the physical world have been so pervasive and invariant throughout humans' phylogenetic or ontogenetic history or both that they may have been incorporated into the operating systems of perceptual mechanisms (Shepard, 1981, 1984). Perceptual representations of that physical world might therefore take account of ubiquitous factors such as gravity.

One way to test such hypotheses involves presenting observers with artificial situations in which a particular physical principle is absent or its expected operations are distorted. If some appropriate measure nonetheless shows that the perceptual representation of these situations contains information indicative of the principle, it can be inferred that this information was imposed by the perceptual system rather than by the structure of the stimulation alone. A variety of experiments involving the use of this strategy have in fact produced evidence that certain environmental properties have become part of the perceptual system, either through evolution or through specific learning throughout a lifetime. Perhaps the classic investigations of this possibility are the mental rotation experiments by Shepard, Cooper, and their colleagues (see Shepard & Cooper, 1982, for summary). These experiments indicate that just as an object moving between two points must cross intervening space, so mental representations of a shift in location also encode the object at intermediate positions. We review further evidence that a variety of universal aspects of the physical environment, such as momentum and gravity, are automatically incorporated in mental models of that environment. Without disputing such evidence, we then raise the possibility that certain representations reflect aspects of perceptual systems that are unrelated to physical properties in the environment. If this is the case, the notion of the direction of influence between the environment and perceptual mechanisms must be expanded.

Momentum

When a braking force is applied to a moving object, the object does not stop instantaneously; rather, it continues beyond the point at which the resistance was encountered. In a variety of experiments, Freyd, Finke, and their colleagues have discovered a mental analog to this physical momentum, which they have termed *representational momentum* (RM). In the basic experimental paradigm used to demonstrate this phenomenon, observers see a series of three static rectangles; the orientations of the rectangles are varied to create an implied rotation. The observers are then shown a fourth rectangle, which is at the same orientation as the third, slightly in front of the implied final orientation, or slightly behind the implied final orientation. The subjects must indicate whether the fourth rectangle is in the same or a different orientation as the third. The subjects make more false-positives—judging the fourth rectangle to be in the same position as the third—when the fourth rectangle is in front of the final location (along the implied rotational direction) than when it is behind (in reverse of that direction; Freyd & Finke, 1984). These results suggest that the subjects' representation of the third rectangle is distorted along

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the path of the rotation, as though the visual system automatically calculates future positions of moving objects on the basis of their perceived trajectory. This calculation seems to be automatic because subjects cannot completely prevent the representational distortion. Further evidence in support of the analogy between physical momentum and RM is that, like the magnitude of the former phenomenon, the magnitude of the latter is influenced in predictable ways by implied velocity (Freyd & Finke, 1985) and by changes in velocity (Finke, Freyd, & Shyi, 1986). For example, the size of the RM effect increases with the apparent velocity of the rotation of the rectangle.

Gravity. In an extension of the RM studies, Hubbard and Bharucha (1988) and Hubbard (1990) presented viewers with circular targets moving either horizontally or vertically on a computer screen. At a certain point, the target disappeared, and the subject had to adjust a cross-hair until it was located directly over the vanishing point. Error patterns were asymmetrical around the vanishing point: The subjects tended to place the point farther along the path of motion. In addition, the forward displacements were correlated with the velocity of the target. These patterns thus replicated standard RM effects. Two additional findings, however, suggest that adjustments for expected gravitational effects also exist in the mental representation of the target's location. First, in the vertical motion condition, more displacement was found when the target moved downward rather than upward. This pattern would be expected given gravitational acceleration as objects move downward and deceleration as they move upward. Second, in the horizontal condition, subjects placed the vanishing point slightly below the correct location, which suggests that a mental analog of gravity distorts the representation of the object downward.

Using more complex, naturalistic displays, Freyd, Pantzer, and Cheng (1988) also obtained evidence that mental representations are altered to account for gravity. In their experiment, subjects were shown displays of a common object that was prevented by a support from falling; for example, a lock would be shown hanging from a hook. In a subsequent display, the object was shown without its prior support. The object was shown in the same vertical position as before, slightly higher, or slightly lower. The subjects were asked to indicate whether the object remained in its original position. Subjects committed more false-positive errors when the object was slightly lower than it was originally compared with when it was higher than it was originally. This result is consistent with the hypothesis that the memory representation of the object's position is distorted downward in the direction of gravity.

In sum, certain perceptual biases and distortions appear motivated when considered in terms of the surrounding physical environment. Indeed, they seem to be internal analogs of external processes or internalizations of statistical regularities in the environment, and they might therefore be very useful in the construction of mental models of the world. Gestalt principles of perceptual organization, such as good continuation, have been interpreted in a similar manner (e.g., Rock, 1983).

Lateral Asymmetry

In this article we explore one type of perceptual organization that seems to be inconsistent with the positions so far presented, in that it appears to be neither an internal analog of the environment nor a necessary part of any representational system with spatiotemporal coherence (and hence corresponds somewhat with the original views of Gestalt psychologists; e.g., Köhler, 1947). Some researchers in the psychology of art have contended that the lateral arrangement of elements within a painting determines some of the perceptual qualities of the painting as a whole. In general, paintings in which action appears to move left to right within a picture are preferred to pictures with the reverse sequence (Freimuth & Wapner, 1979; Mead & McLaughlin, 1991); titles in which the first word refers to left-sided objects, compared with right-sided objects, are preferred (Nelson & MacDonald, 1971); and objects apparently moving left to right are perceived to be accelerating, whereas objects apparently moving right to left appear to be decelerating (Gaffron, 1950; Hansen, 1978). In view of this evidence, and on the basis of prior explorations of acceleration in representational momentum (Finke et al., 1986), greater momentum effects would be expected for rightward than for leftward motion. If such left–right asymmetries exist, it is extremely unlikely that they have an environmental basis, particularly inasmuch as left and right are defined in relation to an observer and are not intrinsic directions in the environment. Nor would Freyd's (1987) more general theory of dynamic mental representations seem to have any particular prediction for memory biases in leftward versus rightward motion.

Hubbard (1990; Hubbard & Bharucha, 1988) is one of the few investigators to have included right and left lateral motion in an RM study. Recall that in his paradigm, subjects tracked a continuously moving object on a screen that then disappeared. His results were equivocal in that usually no lateral effects were found, and a larger leftward than rightward bias occasionally obtained. Although this result contradicts our prediction, Hubbard was not systematically examining such asymmetries, and furthermore the results were not consistent across his experiments; thus strong conclusions from his experiments about the left–right effect are not warranted.

In a preliminary study, Kiff and Halpern (1988) did specifically examine directional effects on representational momentum by presenting a series of three slides, which portrayed an object moving leftward or rightward. After the third slide disappeared, the subjects marked on an answer sheet the remembered final location of the target object. Left–right differences in the expected direction were found: Objects moving to the right were remembered accurately, and a significant *negative* memory distortion occurred for objects moving to the left. However, this methodology was not as controlled as is typical in this type of research, and the long delays involved in a recall task may have contributed to the lack of the standard pattern of RM effects (Freyd & Johnson, 1987).

Nevertheless, this preliminary result was promising enough to prompt us to conduct a series of experiments on left–right effects, using paradigms that are similar to those that have regularly produced the basic momentum phenomenon. We manipulated a variety of factors to determine the consistency of any directional differences in RM. If general, perhaps inborn perceptual principles are responsible for the effect, left–right differences in RM should appear across a range of experimental manipulations. Indeed, such intrinsic principles might be just as basic to perception and representation as the learned internalization of particular physical laws.

General Method: Experiments 1–4

In four of the five experiments to be reported, similar subjects participated, and we used similar stimuli and methods of presentation, and so these are described first.

Subjects

All subjects were Bucknell University students who either volunteered without pay or received partial course credit in return for participation. All subjects used their right hands for writing, carrying, and lifting objects.

Stimuli

We initially chose to use more naturalistic objects as stimuli than has been usual in this type of research. Kelly and Freyd (1987) argued that RM effects are not influenced by real-world properties of objects: that is, that the effect is cognitively impenetrable. We asked the same question about lateral asymmetries in RM. Our best prediction was that results would not depend on type of object, but if they did, we would further investigate which real-world properties of objects affect the results.

Computerized versions of four pictures from Snodgrass and Vanderwart's (1980) study—the rhinoceros, the fox, the motorcycle, and the truck—served as stimulus objects. These were selected because they were depicted in an unambiguous lateral view and could reasonably be expected to move around. We included pictures of animate and inanimate objects that could be expected to move at different velocities in real life. One additional stimulus was the ball, which was modified to be opaque. All the objects were depicted on a horizon line, with a quasi-random background above the line and a gray background below the line (see Figure 1).

A trial consisted of three successive views of the object, displaced to the right or left by 48 pixels (2°) and with specified interstimulus intervals (ISIs). Each view was displayed for 250 ms. This reliably gave a moderately strong impression of movement. (For the purposes of this article, "motion" and "movement" mean *implied* motion and movement.) The fourth view was either identical to the third or was displaced slightly laterally. The period of time between the penultimate and final views was the retention interval.

Procedure

All stimuli were presented on a Macintosh II computer connected to an Apple high-resolution monochrome monitor. Subjects sat 27 in. (68.6 cm) from the screen, and objects subtended a horizontal visual angle of approximately 2°. A trial consisted of presentation of three views of an object, followed by the final view. Using the right hand, subjects pressed one of two buttons on the

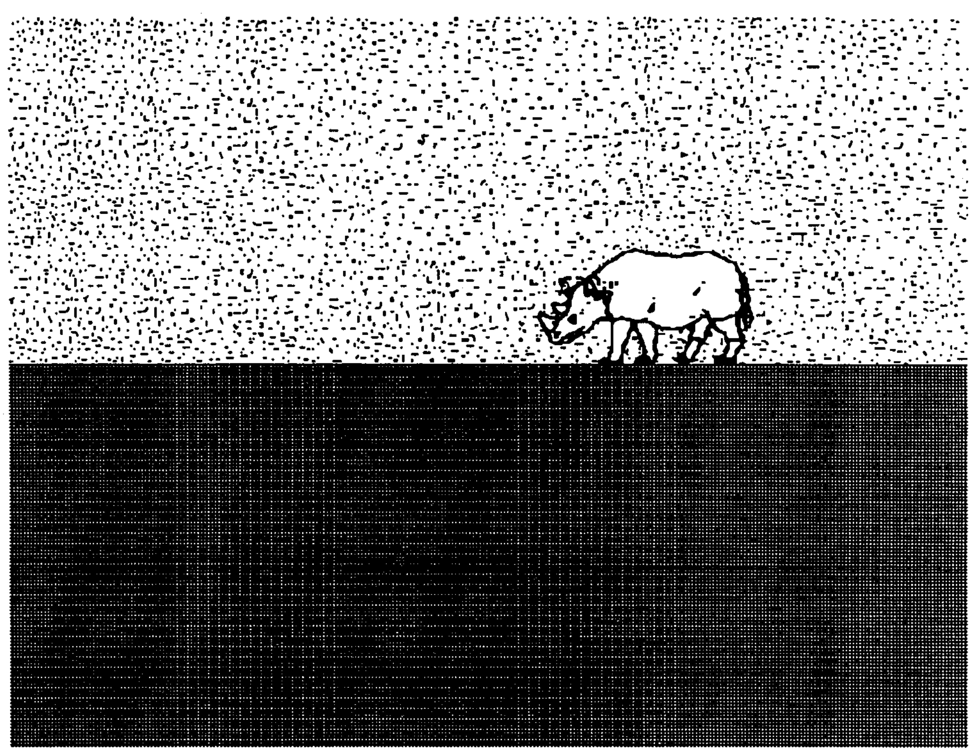

Figure 1. Example of a stimulus. (The rhinoceros was used in Experiments 1, 2, and 3.)

keyboard if the view was the same as the just-seen view and the other button if it was different. The "B" and "C" buttons were used for responding; the identities of the "same" and "different" buttons were reversed for half the subjects in each experiment. Accuracy was the main dependent measure, but reaction times were also collected. All trials were initiated by subjects and were preceded by practice trials.

Experiment 1

In the first experiment, both ISI and retention interval were held constant, and a variety of objects was tested. We predicted that objects moving to the right would induce a larger RM effect than those moving toward the left. Furthermore, objects moving toward the left might induce either no or a negative distortion.

Method

Subjects. Participants were 20 student volunteers. The data of only 19 were analyzed because of near-chance performance by 1 subject.

Stimuli. Objects were the pictures of the fox, motorcycle, rhino, truck, and ball described earlier. ISIs and the retention interval were 250 ms. The first view showed the object near the side of the screen; each of the next two views displaced the object by 48 pixels, or at an implied rate of 4° of visual angle per second. The objects were always facing in the direction of movement (this of course being irrelevant for the ball). Left-moving objects began near the right side of the screen, and right-moving objects began near the left side of the screen. The final object was either identical to the third or was displaced by 0.5°, 1.0°, 1.5°, or 2.0° in or contrary to the direction of motion.

Procedure. Each subject saw only three of the objects: 10 subjects saw the rhino, truck, and ball, and 9 saw the motorcycle, fox, and ball. Except for this, the experimental factors were within subjects. Thus each subject saw three objects, and the final view in one of nine displacements, moving to the right or left, which made 54 trial types. Each trial type was presented four times, which made a total of 216 trials. Subjects were told not to expect equal numbers of same and different trials within the experiment, so as to counter any bias to equalize their responses. The trials were randomly ordered for each subject, and all trials were preceded by five practice trials using objects not seen in the main experiment. The entire session lasted between 15 and 20 min.

Results

Throughout this project, reaction times that differed from a subject's mean by 3 standard deviations were removed from consideration in any analysis. This involved about 2% of the data in each experiment.

Accuracy. The main dependent measure throughout these studies was a memory distortion score that reflected accuracy. We calculated this score from the percentage of times that a subject said "same" for each of the displacements, weighted by the actual value of the displacement (−2 to +2). These numbers were then summed over all the displacements. Recall that only for 0° displacement was "same" the correct answer; all other answers of "same" were errors. Graphs relating the percentage of "same" responses for each displacement are also shown for each experiment (Figure 2).

Each subject received six distortion scores: one for each of three objects moving to the right or the left. Positive values indicate a standard RM effect, or displacements forward in the direction of motion; negative values reflect a reverse momentum effect. In initial analyses, objects were assessed separately; we also combined objects for a more powerful analysis. Figure 2 shows percentage of "same" responses for all objects combined.

Distortion scores were analyzed in separate analyses of variance (ANOVAs) for each stimulus set. Each ANOVA contained the two within-subject factors of direction and object. In the rhino/truck/ball set, positions of right-moving objects (M = 0.99°) were more distorted in a forward direction in memory than were left-moving objects (M = 0.04°) $F(1, 9) = 9.46$, $p < .01$, $MS_e = 22.90$, and the truck produced more distortion (M = 0.82°) than did the other two objects (Ms = 0.32° and 0.40° for rhino and ball, respectively), $F(2, 18) = 6.10$, $p < .01$, $MS_e = 3.78$, but these factors did not interact. For the second set, only the main effect of direction was significant; right-moving objects yielded a score of 0.12°, and left-moving objects, −0.48°, $F(1, 8) = 8.46$, $p < .01$, $MS_e = 9.40$. In this case, however, scores for the right-moving objects were not significantly different from 0°, whereas those for the left-moving objects showed a significant reverse momentum effect.

For every object, the mean signed distortion of the right-moving sequence was larger than that of the left-moving sequence (see Table 1). We performed t tests, which revealed significant differences for four of the five objects: the rhino, truck, fox, and ball (when presented in the same set as the fox and motorcycle). Combining over objects revealed mean distortions of 0.55° for right-moving objects and 0.22° for left-moving objects, $t(56) = 5.72$, $p < .001$. In terms of absolute accuracy, the right distortion was significantly greater than 0° (in a test against 0°, t = 4.72), whereas the left value was not different from 0°. This pattern of significant distortion for the right-moving objects and relative accuracy for the left-moving objects was also true of the rhino, truck, and ball (in that set) considered individually. When we looked at the actual distribution of responses in Figure 2, we saw that subjects were most likely to say "same" when there was in fact no displacement. However, the curve for the right-moving objects is clearly displaced to the right of the graph in relation to that for the left-moving objects, this shift is equivalent to the forward memory distortion reflected in the derived score.

Reaction times. Reaction times were first inspected for speed–accuracy trade-offs. Reaction times were correlated with each subject's errors for each object. Considered separately, the correlations were low and negative, ranging from −.33 for the rhino (df = 161) to −.09 for the truck (df = 144) and a ball (df = 150). Combining over objects yielded a correlation of −.15. Although the negative values

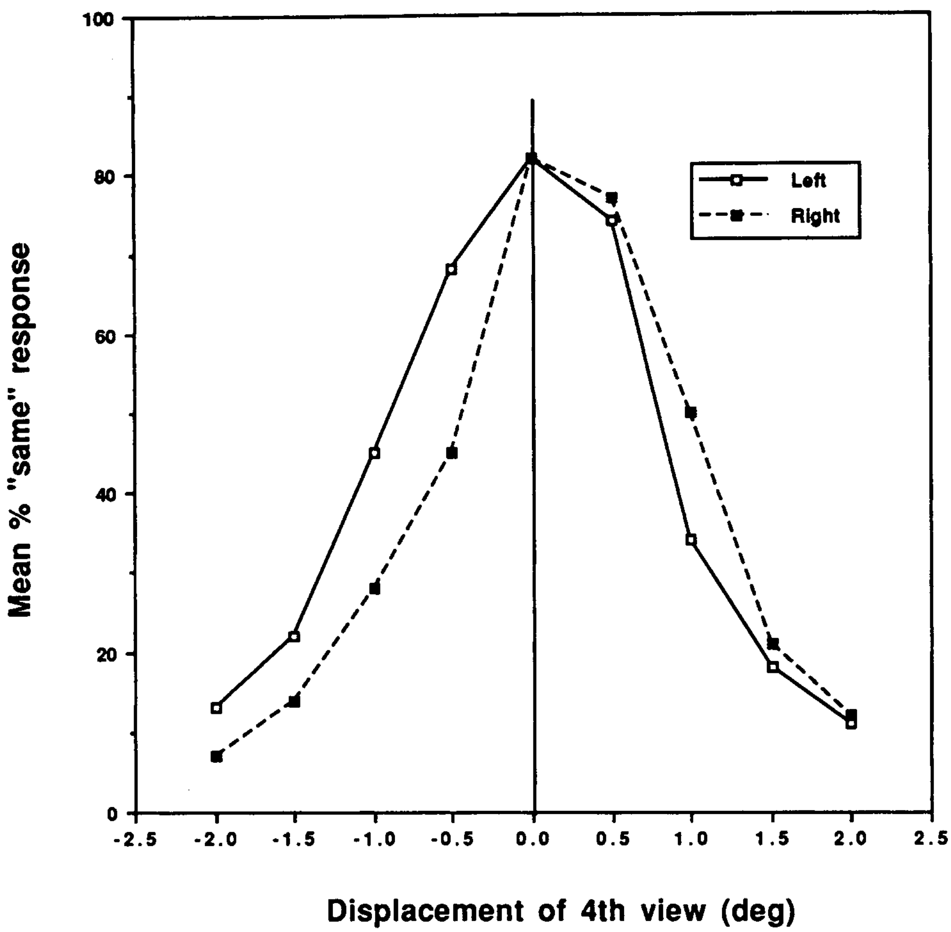

Figure 2. Percentage of "same" answers for each displacement for all objects combined in Experiment 1. (Left- and right-moving objects are shown by separate lines.)

might suggest a speed–accuracy trade-off, for no comparison was the correlation significantly different from 0, even with many degrees of freedom. Even for the rhino, only 11% of the variance in reaction time was accounted for by errors.

In the next set of analyses, we investigated whether reaction time changed systematically with direction, object or object set, and displacement. We did not expect such a relation with displacement after failing to find a speed–accuracy trade-off, but there existed the possibility that reaction time might vary with the other factors. Two types of ANOVA were performed: one involved the between-subjects factor of object set and the within-subject factor of displacement and direction; the other involved each object. Analyses were performed on log-transformed reaction times.

Virtually no effects were found in any of these analyses. The overall analysis showed a significant displacement effect, $F(8, 416) = 2.97$, $p < .01$, $MS_e = 0.13$, which is accounted for by dips in reaction times at 0° and −2° displacement. However, the only object for which this dip was significant was the truck, $F(8, 72) = 2.41$, $p < .05$, $MS_e = 0.08$. A marginal three-way interaction in the overall analysis, $F(8, 416) = 1.86$, $p = .07$, $MS_e = 0.11$, suggests the absence of this dip for the left-moving objects in the motorcycle/fox/ball set. The only remaining

Table 1
Mean Distortion Scores (in Degrees) for Each Object in Experiment 1

Object	Left distortion	Right distortion	T value for difference	*df*
Set 1				
Rhino	−0.20	0.84[a]	2.30[b]	9
Truck	0.34	1.30[a]	2.54[b]	9
Ball	−0.02	0.82[a]	1.94	9
Set 2				
Fox	−0.52	0.22	2.30[b]	8
Motorcycle	−0.34	−0.04	1.41	8
Ball	−0.60	0.18	2.46[b]	8
Sets combined	−0.22	0.55[a]	5.73[b]	56

[a] $p < .05$ for the *t* test against 0° distortion. [b] $p < .05$ for the *t* test for the difference between the left and right distortion scores.

even marginal effect was longer times for left-moving versus right-moving rhinos, $F(1, 9) = 4.38$, $p = .07$, $MS_e = 0.13$.

Discussion

Objects moving to the right are in fact remembered as having moved forward in the direction of motion more than are objects moving to the left. Although not established for every object in every condition, the majority of individual comparisons as well as the combined result support this view. When the absolute RM effects were considered, the overall result was, again, positive memory distortions for right-moving objects and accurate memory for left-moving objects. However, for a subset of objects, the same result found by Kiff and Halpern (1988) was obtained: relative accuracy for right-moving objects and a negative distortion for left-moving objects. We cannot explain why this alternative result is occasionally found; however, the important point for our purposes is that the relation between distortions to the left and the right is preserved in both the usual and less usual patterns of results.

No effects of interest seemed to depend on animacy or speed characteristics of the particular objects being used. For instance, fast, motor-powered motorcycles and trucks did not produce more bias than slower, food-powered foxes and rhinos. This suggests that observers were not using their background knowledge extensively in formulating their judgments. We did find that the two stimulus sets differed in the extent to which they elicited the lateral asymmetry. Indeed, the ball was common to both stimulus sets, and it elicited both patterns of results (forward distortion/accuracy or accuracy/negative distortion). Perhaps subjects were allowing real-world mass to influence their judgments. In fact, the truck/rhino/ball set, containing large objects in the real world, produced larger distortions overall than did the smaller objects in the motorcycle/fox/ball set. If this were generally true, however, the rhino should have produced more distortion than did the ball in the former set, and the motorcycle should have produced more distortion than the fox, which, in turn, should have produced more distortion than the ball in the second set. Neither result obtained. We may be forced to attribute this difference in results to unspecified characteristics of the two subject groups.

The reaction time analysis was not extremely informative. However, because a slight trend toward a speed–accuracy trade-off was observed, reaction times were analyzed in the next experiment, whereas accuracy remained the main dependent measure.

The significance of the results of this first experiment is twofold. First, we have shown that the current methodology is sufficiently sensitive to show the standard RM effect. Second, we have demonstrated a phenomenon that cannot be accounted for by a simple internal analog of real-world laws or other theories so far advanced in the RM literature. In the next experiment, we sought to replicate the basic left–right result found in Experiment 1. In addition, we began to investigate other factors that might modify these results.

Table 2
Mean Distortion Scores (in Degrees) for Each Interstimulus Interval (in Milliseconds) in Experiment 2

Interstimulus interval	Left distortion	Right distortion
100	.24	.54
250	.22	.50
500	.28	.58
1,000	.06[a]	.56

[a] Only value *not* significantly different from 0° distortion.

Experiment 2

In this experiment, we varied the implied velocity of the objects by varying the ISI between the first and second views and between the second and third views. The retention interval between the third and fourth views was held constant. If the left–right effect were influenced by implied velocity, its magnitude should increase with increasing ISI. We expected all results to generalize over the different objects.

Method

Subjects. Participants were 18 student volunteers. The data of only 17 were analyzed because of near-perfect performance by 1 subject.[1]

Stimuli. The pictures of the rhino, truck, and ball from Experiment 1 were used, but only the seven displacements from −1.5° to +1.5° were used for the fourth view. Four ISIs were tested: 125, 250, 500, and 1,000 ms. These translated into implied velocities of approximately 5.3°, 4.0°, 2.7°, and 1.6° per second, respectively.

Procedure. ISI, direction, and object were all within-subject factors. The three objects, two directions, four ISIs, and seven displacements yielded 168 trial types. Trials were blocked by objects; each object occurred equally often as the first, second, or third block in the session. Each trial type was presented three times in a different random order for each subject, which yielded a total of 504 trials; each subject received 10 additional practice trials. The session lasted between 40 and 50 min. A short break occurred between each block, and of course subjects were free to rest at any time because the trials were self-initiated.

Results

Accuracy. Distortion scores were calculated as in Experiment 1. The effects of object, direction, and ISI on these scores were assessed in an ANOVA. As expected, no effects depended on the object used, and so Table 2 shows

[1] We chose to exclude from analysis the 2 subjects from Experiments 1 and 2 who showed near-chance or near-perfect performance. When a memory illusion is investigated, a participant not subject to the illusion or failing to perform the task does not add any data relevant to the question at hand.

the means of each ISI/direction combination. Figure 3 shows the percentage of "same" responses for each displacement in each of the ISI conditions.

As can be plainly seen, the only significant effect was the greater distortion of the right-moving objects (M = 0.56°) as compared with that of the left-moving objects (M = 0.24°), $F(1, 16) = 27.44$, $p < .001$, $MS_e = 3.41$. This occurred at each ISI, so that ISI yielded no main effect, nor did it interact with direction of motion.

With regard to the magnitude of the distortions, both right- and left-moving objects at each ISI yielded a forward distortion significantly different from 0° (ts ranged from 2.42 to 7.77), with the exception of the left-moving objects at the 1,000-ms ISI, which yielded no distortion.

Reaction times. Speed–error correlations were calculated for each object individually and were combined over objects. Correlations were positive this time but still very low and nonsignificant, ranging from .06 for the truck to .17 for the objects combined.

In a subsequent ANOVA, we examined effects of displacement, ISI, and direction on log-transformed reaction times. For ease of interpretation, analyses were conducted separately for each object. One finding for all three objects was a slower reaction time for right- than for left-moving objects: For the ball, $F(1, 16) = 11.48$, $MS_e = 0.60$; for the truck, $F(1, 16) = 34.18$, $MS_e = 0.28$; for the rhino, $F(1, 16) = 26.65$, $MS_e = 0.25$ (all ps $< .001$). This is congruent with the small positive correlation between errors and speed; that is, subjects' responses were slower as well as less accurate for the right-moving objects. The only other interpretable and consistent result was that the −1.5° displacement elicited the fastest reaction time in comparison with the other displacements. Main effects for the displacement factor were $F(6, 96) = 6.20$, $MS_e = 0.13$, for the ball; $F(6, 96) = 5.73$, $MS_e = 0.11$, for the truck; and $F(6, 96) = 3.83$, $MS_e = 0.11$ for the rhino (all ps $< .001$). Again, this is congruent with the finding that almost all objects produced a positive memory distortion. Thus subjects were both quick and accurate in rejecting as "same" a final view that was so obviously contrary to the path of motion of the sequence.

Discussion

This study replicated the most striking result of Experiment 1: Right-moving objects engendered a stronger memory bias than left-moving objects. In fact, the replication was nearly exact for the right-moving objects (a distortion of 0.55° in Experiment 1 and 0.56° in Experiment 2). In this experiment, all conditions except one showed a forward

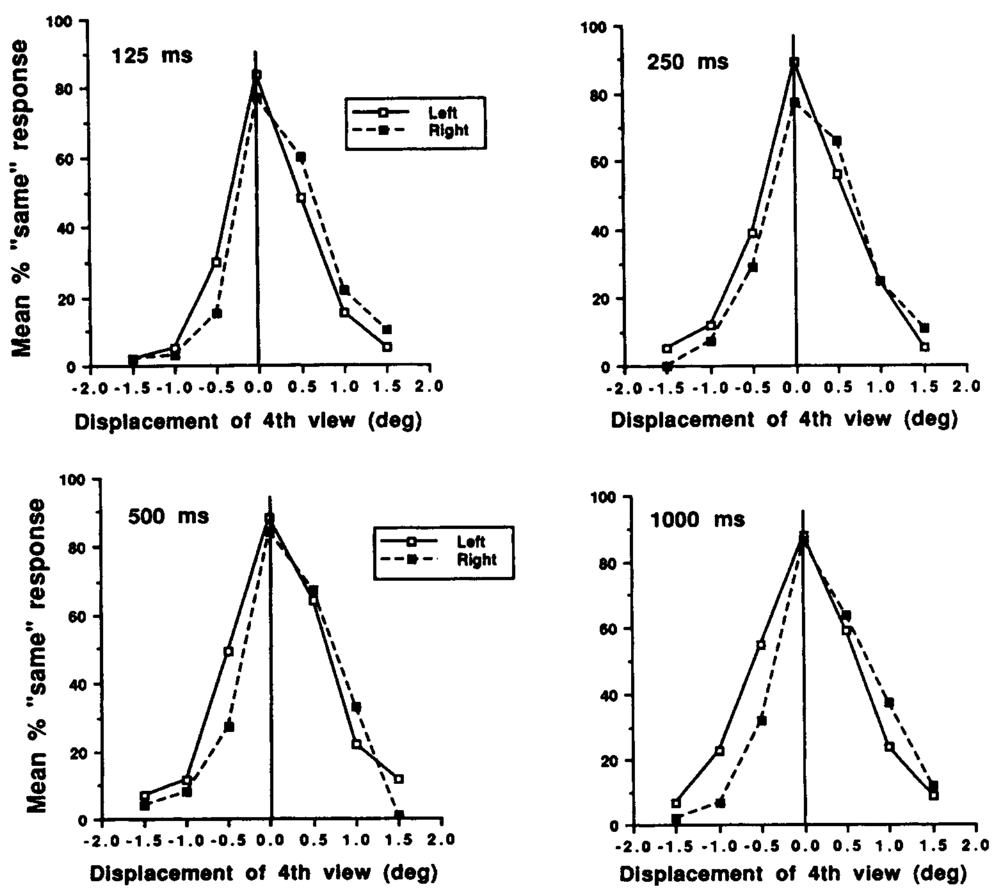

Figure 3. Percentage of "same" answers for each displacement for all objects combined in Experiment 2. (Each interstimulus interval is shown in a separate panel.)

memory bias; that is, no negative memory distortions were observed. Thus our methodology seems to be sufficient to show the basic RM memory distortion.

We found no evidence that the left–right effect is influenced by the real-world properties of the objects used as stimuli. In Experiment 2, the truck, rhino, and ball yielded identical results.

An unexpected null finding was the lack of influence of ISI on the extent of forward memory distortion. In contrast to findings in previous research, increasing apparent velocity did not increase the memory bias, although, we should note that, our implied velocities both were slower and encompassed a narrower range of values than those of Freyd and Finke (1985). In general, because we did not find the usual ISI effect, we must consider the possibility that the left–right difference in memory performance may not be identical to RM. The basic result of a forward memory bias looks very much like the biases found in previous work, but perhaps some additional mechanism associated with the left–right effect was operating in such a way as to modify previously robust influences of apparent velocity. To be cautious, we henceforth refrain from labeling our effect a simple manifestation of RM. Instead, we use more general terminology, such as *left–right memory biases*, as in the title of this article.

The reaction time analysis was again not particularly useful. The small positive speed–error correlations served to allay any fears that a speed–accuracy trade-off might have been a significant influence on the results of Experiment 1. Because of their limited informational value, reaction times are not reported for future experiments except in instances when significant speed–accuracy trade-offs emerged.

In the next experiment, we continued the investigation of the basic parameters of the left–right effect. Retention interval was selected as the next factor of interest.

Experiment 3

In this experiment, we kept ISI constant and varied retention interval (RI). We again expected the left–right difference, which should again generalize over objects. Freyd and Johnson (1987) found that the magnitude of the RM memory distortion in a rotation paradigm increased with RIs of up to about 300 ms and then decreased with longer RIs of up to about 1 s. They proposed that RM mechanisms were operating over the short term but that with longer RIs, subjects mentally average all the stimuli in a sequence, which would lead to a negative memory shift. The combination of the positive memory shift in RM and the negative shifts of the averaging operation cause the reduction of the distortion at the longer intervals.

Our paradigm was quite different from Freyd and Johnson's (1987), and so we could not predict that our effect would show exactly the same time course as did theirs. We did predict an overall change in the memory bias with increasing RI (main effect of retention interval). If the longer RI leaves more time for the mechanism underlying the left–right effect to develop, an interaction of direction of motion with RI would be seen.

Method

Subjects. The subjects were 30 students from the same pool as in previous studies.

Stimuli. The rhino, ball, and truck were used again in this experiment. The range of displacements for the fourth view was again $-1.5°$ to $+1.5°$. The ISI was held constant at 250 ms, but the RI was either 125 or 500 ms. These values, together with the 250-ms RI in Experiment 2, cover the range of RIs in which the RM effect increased and then decreased in Freyd and Johnson's (1987) experiment.

Procedure. To facilitate a comparison with Experiment 2, the RI was varied between subjects. Otherwise, the procedure wasthe same as in Experiment 2; trials were blocked by objects. Each of the 14 trial types per object was presented three times, yielding a total of 126 trials per subject. Each subject received 10 practice trials with the appropriate RI. The session lasted between 10 and 15 min.

Results and Discussion

Figure 4 shows shows the percentage of "same" responses for each distortion in each of the RI conditions. In the main analysis, the ANOVA for the distortion scores revealed the usual greater distortion for right-moving objects ($M = 0.53°$) than for left-moving objects ($M = 0.28°$), $F(1, 88) = 9.6$, $p < .01$, $MS_e = 3.04$. The magnitudes of these distortions were nearly identical to those in Experiment 2. Neither a main effect of RI nor an interaction of the two factors was observed, although the interaction was somewhat suggestive ($p = .08$) of an increased left–right effect for the longer RI. An informal comparison with the appropriate condition from Experiment 2 (250-ms ISI and RI) is pictured in Figure 5 and further suggests a relation between RI and magnitude of the left–right effect.

Again, all right-moving objects produced more memory distortion than did left-moving objects, and as in Experiment 2, both the left- and right-moving objects produced forward distortion in the direction of motion (all $ps \leq .057$).

Once again, the basic left–right effect was replicated, which increased our confidence in its robustness. We found no main effect of RI, which previous work in RM had led us to expect. Certainly our results showed no similarity to Freyd and Johnson's (1987) inverted U function relating the amount of distortion to RI. We thus continue to be circumspect in calling our effect a pure manifestation of RM, although the results may indicate that the effects are strongly related. We did find a trend toward an increasing left–right effect with increasing retention time. Figure 5 suggests that the rightward memory bias is more influenced by the increased RI than is the leftward bias. Perhaps if the RI had been increased even further, the trend in these results would have proved to be reliable.

Experiment 4

The previous three experiments appear to give ample evidence of the reliability of the left–right effect. However, one potential confound had to be addressed before our confidence would be complete. In all the previous experiments, objects moving to the right started out on the left side of the

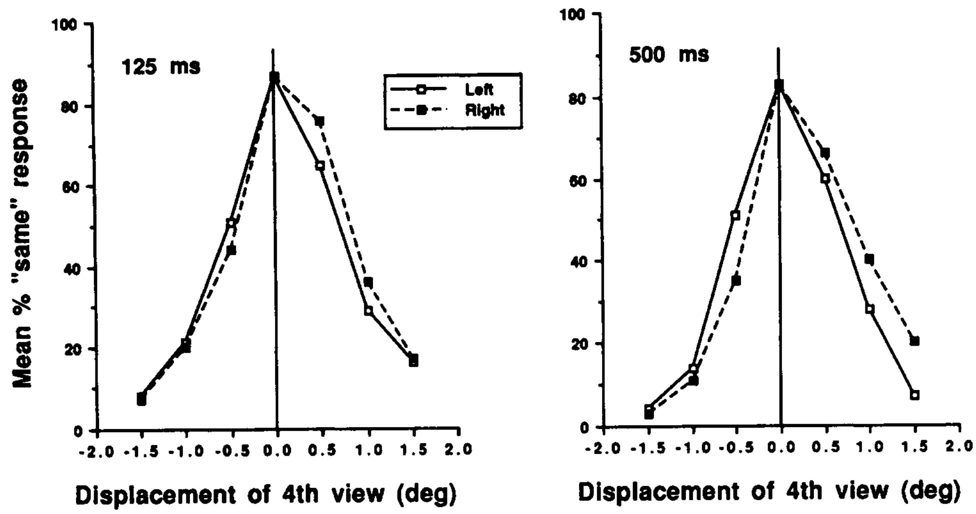

Figure 4. Percentage of "same" answers for each displacement for all objects combined in Experiment 3. (The two retention intervals are shown in separate panels.)

screen, and objects moving to the left started on the right side of the screen. We needed to cross left and right motion with left screen and right screen placement to eliminate the possibility that the left–right effect is really a left screen right screen effect. This was the purpose of Experiment 4. If our previous results were caused by the side of screen that subjects were viewing, we would expect greater memory distortions for objects in the left half-screen than objects in

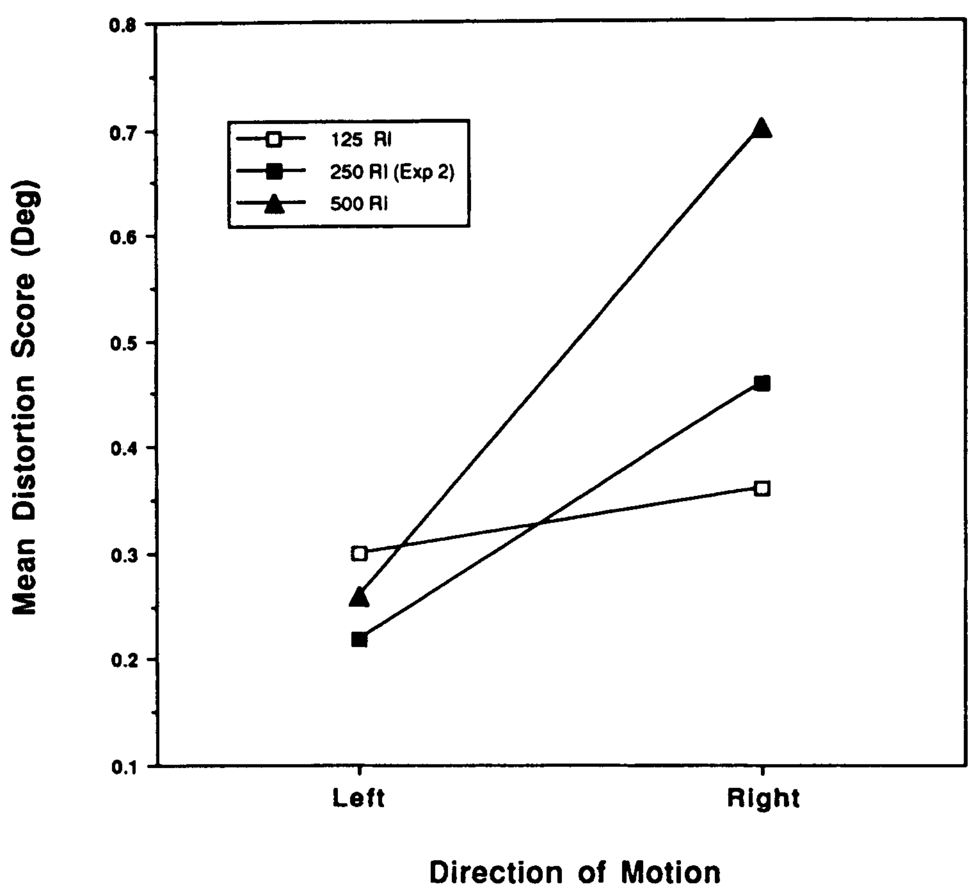

Figure 5. Mean distortion score at each retention interval for each direction in Experiment 3, combined over objects. (The 250-ms condition from Experiment 2 is included for comparison.)

the right half-screen, regardless of direction of motion. Naturally, we hoped not to find this result and instead predicted that the left–right effect would obtain in both screen halves.

Method

Subjects. Twenty students participated as subjects.

Stimuli. Because type of object did not seem to affect the results in the previous experiments, we used only the ball in this study. Both the ISI and RI were 250 ms, and we used displacements from −1.5° to +1.5° for the last view. The new factor introduced in Experiment 4 was screen placement. The first view in each sequence was placed one quarter the way from the right edge or left edge of the screen. Each sequence could move to the right or the left in the right or left half of the screen. Thus the two directions, two screen halves, and seven displacements yielded 28 trial types. Each trial type was presented three times, yielding a total of 84 trials for each subject; all factors were within subjects, and all trials were randomly intermixed. The session lasted approximately 10 min.

Results and Discussion

Figure 6 shows the percentage of "same" responses for each distortion in each of screen and direction combinations. Putting to rest the possibility that our previous results were caused by a confound, side of screen had no overall effect on the results (*M*s = 0.02° for left half of screen and 0.05° for right half of screen). However, neither did direction of motion, for the first time in this series! Instead, as Figure 7 clearly conveys for the distortion scores, there was a Direction × Screen Side interaction, $F(1, 19) = 8.72$, $p < .01$, $MS_e = 0.57$. Further analyses showed that the by-now-usual left–right effect obtained in the left half of the screen, $t(19) = 6.16$, $p < .001$, judgments of movement in both directions being significantly different from 0° distortion ($p < .001$), but direction of motion did not have an effect in the right half of the screen, and neither value differed from 0° distortion.

We essentially replicated the major result here in two other pilot studies in which the initial view of objects moving toward the center of the screen started at the edge of the screen, and objects moving toward the edges started one quarter of the way from the screen edge, as in Experiment 4. In both cases, the left–right effect was seen in its usual form in the left half-screen and was eliminated in the right half-screen.

Thus we can conclude that our results in Experiments 1–3 were not caused by the positioning of the sequence on the screen. The left–right effect was reliable, but apparently only for left-side presentation. We cannot conclusively claim this as a visual field difference, because subjects were allowed to use unconstrained eye movements at all times. However, because all trial types were randomly intermixed, an efficient subject would probably have adopted a strategy of attending to the middle of the screen as he or she initiated the trial. If so, the first stimulus view would have in fact occurred in the left or right visual field as well as left or right screen half, and the memory bias would be more pronounced when the right hemisphere (processing the left visual field) initially receives the information than when the left hemisphere is the first recipient. We return to this neuropsychological issue in the next experiment and the General Discussion.

Experiment 5

The apparent confinement of the left–right effect to the left screen side was an unexpected result, perhaps indicating a general propensity for right-handed subjects to process visual information more accurately in the right half than in the left half of visual space. We undertook Experiment 5 as a control experiment to see whether a simple perceptual task would show such an advantage. This task did not involve implied motion; instead, we simply asked subjects to indicate the position of a briefly presented target in the right or

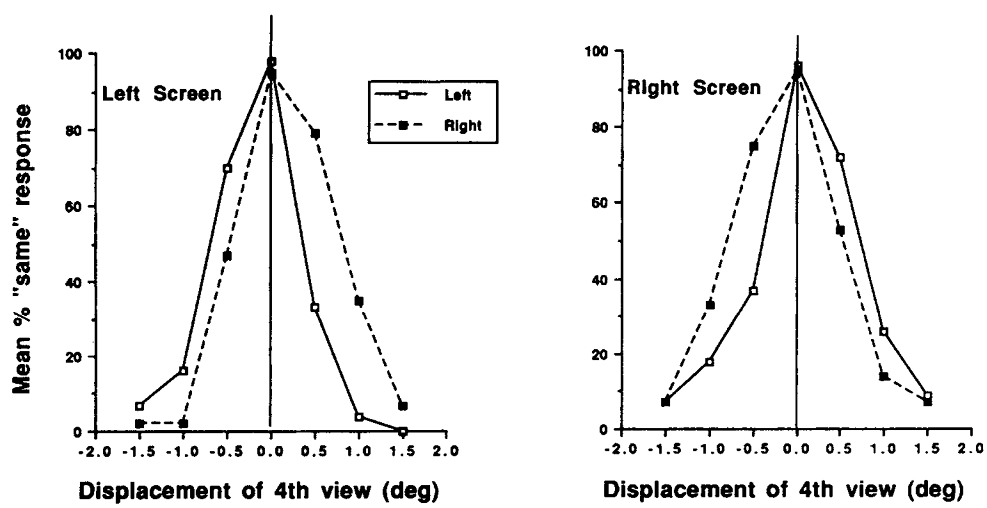

Figure 6. Percentage of "same" answers for each displacement in Experiment 4. (Each screen side and direction of motion is shown separately. Data from one of the 20 subjects were unavailable for inclusion in the figure.)

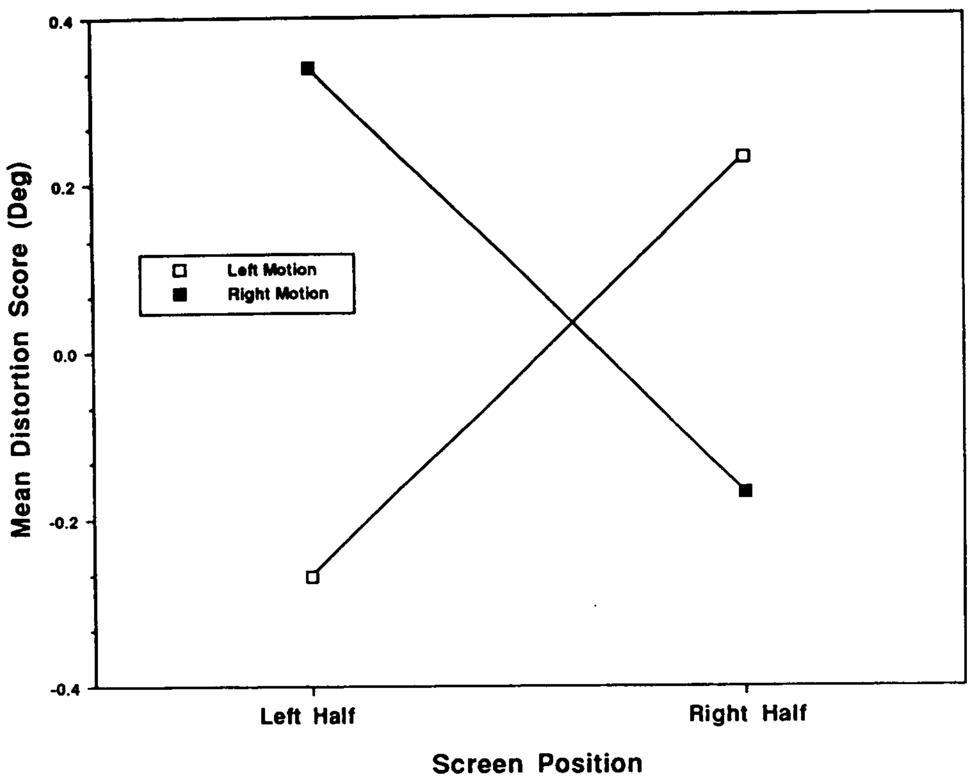

Figure 7. Mean distortion score for each direction and screen side in Experiment 4.

left field. Of primary interest was whether targets were more accurately localized in one half screen or the other under exposure conditions similar to those used in our main experiments. If so, the results from our previous experiments might have little to do with implied motion and instead might reflect a basic perceptual asymmetry. Of secondary interest was the absolute accuracy of response and whether any constant errors might be displayed.

Method

Subjects. Twenty-four Bucknell University students participated in this study. All were right-handed.

Stimuli. This task was quite different from that in the previous four studies, although it too was run on a Macintosh II computer. The target on each trial consisted of an uppercase letter O in 24-point boldface Courier type, which was presented on a white background. The vertical position of the target was in the middle of the screen in all trials. The horizontal location was determined randomly for each trial, and the center of the target could occupy any of the central 512 horizontal pixel locations (of a total of 640 horizontal pixel locations).

Procedure. On each of 100 trials, subjects were first presented with a warning phrase, "Prepare for the next trial." This phrase was centered on the screen and was displayed for 1.5 s. After a blank interval of 1 s, the target was presented for 250 ms. Subjects were instructed to guide the center of a cross-hair over the location where the target had disappeared and then to click on the mouse to indicate the center of the recently displayed target. Because of the brevity of the target, subjects never had time to effect the mouse response while the target was still visible. The warning signal for the next trial appeared immediately after the response to the previous trial. Accuracy rather than speed was emphasized, and no time limit was set for responding. Sessions lasted between 10 to 15 min.

Results and Discussion

Scoring. On each trial, the computer recorded the actual location of the target's center and the horizontal and vertical deviation between the actual location and the estimate given by the center of the cross-hair. All results are reported in terms of pixels. Negative horizontal deviations indicate that a subject's estimate was to the right of the true position whereas positive errors indicate that the estimate was to the left of the true position. Negative vertical deviations indicate that a subject's estimate was below the true position, whereas positive errors indicate that the estimate was above the true position.

Accuracy. The main result of interest is the horizontal deviation in each screen half. Subjects' responses were relatively accurate on the average: The mean horizontal errors were −1.78 pixels (SD = 3.75) in the left half-screen and 2.11 pixels (SD = 2.85) in the right half-screen. These differed significantly both from each other and from 0. In other words, subjects made small horizontal deviations toward the center of the screen. With regard to the absolute value of each subject's deviations, errors did not differ in the two screen halves (Ms = 3.14 and 2.90 pixels in the left and right, respectively). The average vertical deviation was −5.55 pixels (SD = 1.61). All subjects produced negative vertical deviation scores, which means that the target was localized below its actual position. This is consistent with the results by Hubbard and Bharucha (1988) and Hubbard (1990), suggesting the operation of the gravity principle in localizing an object's position.

This control experiment demonstrated that in the absence of implied motion, the right and left screens do not differ in interesting ways in eliciting a perceptual bias in target location. Subjects responded equally accurately in both half-screens, but they showed a slight tendency to locate targets closer to the center of the screen than they actually were. This could be accounted for any number of principles, such as a preference for avoiding edges or some kind of perceptual averaging. Thus, to account for the side of screen effect in Experiment 4, we needed to postulate something more than a basic asymmetry in efficiency of localizing static visual targets. Apparently, the presence of implied motion is one of the necessary added ingredients.

One point that we needed to address before concluding was whether our results could be completely accounted for by the slight to-the-center bias found here, a bias that was for some reason more pronounced on the left side of the screen. In Experiments 1–3, the rightward (centerward) motion was of course on the left side of the screen; might this account for the exaggerated memory illusion?

This alternative suggestion cannot fully account for our findings, however. The to-the-center bias in Experiment 5 was no more pronounced on the left than on the right side of the screen. In addition, the notion of such a bias cannot account for the times when the rightward motion was remembered accurately and the leftward motion engendered a reverse bias. Finally, why would such a bias be stronger on the left than the right side of the screen (actually, according to Experiment 4 and its replications, there was no bias at all on the right side)? Thus the to-the-center bias explanation accounts for somewhat fewer data than our formulation and leaves us with the same explanatory puzzles discussed next.

General Discussion

In our introductory remarks, we raised the possibility that certain kinds of internal representations reflect biases that could not have been derived from learning about the physical world. We believe that we have established one such effect. To recapitulate the main results: Objects apparently moving toward the right produce a larger memory distortion in the direction of motion than do objects moving toward the left. The lateral asymmetry may be evident in only the left half of visual space. Even so, the stark contrast is with real-world motion, in which left- and right-moving objects have identical characteristics. This result generalizes over a variety of objects, ISIs, and (possibly) RIs. It even generalizes over method of presentation and response, because results from the slide presentation and recall task in Kiff and Halpern's (1988) study were essentially replicated in our series using computer presentation and a recognition response.

This generalization not only serves to establish the reliability of the phenomenon but also serves our theoretical argument. It could be argued, for instance, that the basic effect results from a learned internalization of motion, as depicted in artworks. If so, it might be predicted that the magnitude of the effect would be subject to the same constraints seen in the types of RM that are also learned from the real world. For instance, faster apparent velocity and longer RIs should increase the effect, regardless of how it originally came to be. But we found no evidence for the former and only weak evidence for the latter. The left–right effect seems decoupled from real world referents in both its origin and dynamics.

The logical question to ask is, What might be responsible for this lateral asymmetry, if not a real-world analog? We consider three possibilities. One obvious source is reading habits. All our subjects were native readers of English. Morikawa and McBeath (in press) recently provided evidence that reading style can in fact affect visual perception. They presented a row of diamond shapes separated by blank spaces. In a second display, following immediately, the same shapes were presented but displaced in such a way that the midpoint of each shape in the second frame was centered where blank space had been before, and vice versa. The percept was of the whole row of diamonds moving to the right or the left, but physically the direction of motion was ambiguous. Morikawa and McBeath found a strong bias among samples of Americans and Japanese to see motion to the left. This bias disappeared for a sample of participants whose native language was read right to left (although each was also fluent in English or French). The authors suggested that rightward saccades place information in the left visual field and that this predisposed the Americans and Japanese to see the leftward motion. They speculated that a group of monolingual Arabic or Farsi readers would show a tendency to see motion to the right.

Although this finding is interesting and robust, it does not seem to be congruent with our left–right effect. In our study, subjects were presumably making accurate saccades to all the views in the sequence (in all but two conditions across the experiments, at least 250 ms elapsed between the views of a sequence, allowing enough time for eye movements). If subjects have a tendency to see motion to the left when making saccades to the right, the first three views should be remembered as being slightly to the left in comparison with where they really were. Thus subjects should tend to judge the view slightly to the left of the actual third view as being identical to it. In other words, Morikawa and McBeath's (in press) findings would, if anything, suggest a reverse momentum effect for both left- and right-moving sequences (the same logic should apply to both sequence directions).

Perhaps some other aspect of reading habit can account for our results. For instance, readers of left-to-right languages are used to scanning ahead when tracking something moving from left to right but not something moving from right to left. This "overshoot" in left-to-right reading might generalize to other tracking of visual objects and thus may cause such readers to remember the third view as being located farther to the right than was actually the case. Left-moving sequences might elicit accurate scanning, thereby reducing or eliminating the tendency. Similarly, eye movement studies have shown that during a reading task, readers of English are affected by information at least eight letters to the right of fixation but by fewer than four letters to the left of fixation (Rayner, Well, & Pollatsek, 1980; Underwood & McConkie, 1985). In other words, the attentional field is asymmetrical, with an expanded field to the right. This expansion of the attentional field might lead to extrapolation of apparent motion to the right more than to the left.

To investigate both of these possibilities further, researchers would need to measure eye movements during our task or test readers of right-to-left languages, or both. Indeed, Pollatsek, Bolozky, Well, and Rayner (1981) found that among Israelis, the visual attentional field was expanded to the left while reading Hebrew but to the right while reading English. Although reading habits may partly account for our results, we are not convinced that this is a full explanation because of some cross-cultural evidence, to be discussed, regarding depiction.

A second possible explanation for our results concerns hemispheric specialization. Because information from each visual field is initially processed by the opposite hemisphere, perhaps differential attention to each side of space can account for our results, particularly in light of the side of screen effect in Experiment 4. Levy (1976) made just such an argument after finding that right-handed observers favored pictures in which the most important figures were on the right or that seemed to be "heavier" on the right. Left-handed observers, who on the average have less functional asymmetry in brain function, did not show these preferences. Because the spatially dominant right hemisphere in right-handed persons is the one that initially processes the left spatial field, it might be expected that paintings heavier on the *left* would be most admired. Levy, however, suggested that viewers might prefer "balance" in pictures, in which case the placement of greater importance or heaviness on the right side of the picture might balance the inherent attention toward the left.

Although Levy may have been correct, this line of reasoning strikes us as being rather ad hoc, because either pattern of preference (for left- or right-weighted pictures) could have been explained under the same scheme. A more precise investigation of this possibility could use the methodology that we used, presented to people whose functional laterality has been established by certain well-known tests of dichotic listening. With sufficient time and population resources, researchers could, for instance, gather a population of left-handed subjects (about 10% of the general population) with typical left-hemisphere speech dominance (about 70% of that population), reversed speech dominance (15%), and bilateral speech representation (15%). Any differences in our tasks across these subject groups could then be attributed more securely to a particular aspect of brain organization. Any neuropsychological explanation would need to account for the fact that it was in the left half of the screen and (presumably right-hemisphere mediation), that performance was less accurate: that is, showed the stronger memory illusion.

Finally, we consider the possibility, mentioned earlier, that the left–right effect develops from a learned internalization of motion as depicted in artworks. The argument might be that because people are exposed to art from an early age and over many years, they have developed scanning habits and other strategies that would reinforce the notion that right-moving elements are more dynamic. But this notion is not very tenable on pragmatic grounds, in view of the amount of time that an average American undergraduate spends looking at artwork, in comparison with all the hours watching real motion that does not distinguish between right and left.

This possible causal path also begs the question of the origin of those depicted asymmetries. For instance, some authors have speculated that rightward motion in art is related to reading habits, but in fact certain rightward biases in depiction occur in cultures with other reading patterns. Kelly (1992) surveyed paintings from Chinese, Japanese, Indian, and Persian traditions, as well as Western art. He found that in all the cultures, important elements tend to be placed to the left of less important elements. Braine, Schauble, Kugelmass, and Winter (in press) examined how children from various cultures depict depth in their drawings. Americans reliably put near objects to the left of far objects. But contrary to the simple prediction that left-to-right reading habits affect this convention, Hebrew readers also showed the same pattern, as did Arabic children in the seventh grade. Younger Arabic-reading children were the only ones to show a preference in drawing near objects to the right. The authors speculate that an inborn disposition to attend from left to right is temporarily suppressed during learning of Arabic (which not only is read from right to left but the letters of which are also formed from right to left, unlike in Hebrew) but then emerges when the right-to-left sequence in reading no longer commands the considerable attentional resources expended by a novice reader.

If the left–right effect does not develop from a learned internalization of motion in art, the other remaining causal path is at least equally intriguing. If in fact we have identified some internal constraints that are not derived from external constraints, then perhaps the right-motion bias shown by artists derives not from their internalization of the external world but rather from the externalization of their internal world.

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