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Representational momentum when attention is divided

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Observers tend to misremember a transforming object's final appearance as further along in the direction of continued transformation. This forward bias, termed representational momentum (RM), suggests that the dynamics associated with an object cannot be ignored in the effort to remember a particular instance of the object. Two experiments tested how attentional focus affects this memory bias. Observers attended to one object, divided attention across more than one object, or performed a secondary task simultaneously with the RM task. For objects translating in space, diminished attention increased the forward memory shift, suggesting that under distraction, motion can be represented but the stopping point is less effectively represented. We propose that object dynamics are well represented when attention is distracted, but that representing a change—including stopping—in the dynamics requires attention. We suggest some experiments to examine this proposal further.

Much of everyday life is spent moving about in the world, and planning or avoiding contact with other moving objects. Such facility in interacting with the world clearly requires that we maintain some sense of what the people and things around us are doing. In other words, we must in some way perceive and represent the dynamic information associated with the various entities in our environment. Typically, this task must be accomplished as we flexibly turn our attention to a multitude of different objects and goals. The present experiments use the representational momentum (RM) task developed by Freyd and Finke (1984) to explore how attention affects the perception of dynamic events.

In a RM experiment, observers view a stimulus that undergoes some type of transformation. Typically, the transformation is implied in a series of static images, thus eliminating low-level motion cues. Observers attempt to remember the final presentation of the stimulus. After a short retention interval, usually ranging from 50 to 400 ms, observers perform a recognition memory task on a probe stimulus. The fundamental result is that observers have greater difficulty rejecting probes that are too far forward in the direction of transformation than those that are too far backward. This bias suggests that memory for the final presentation is influenced by the depicted dynamics of the display, and the magnitude and direction of the memory shift is taken as a measure of the represented dynamics associated with the object under view.

Representational momentum has been investigated in a variety of contexts, such as auditory pitch change (Freyd, Kelly, & DeKay, 1990; Hubbard, 1995; Kelly & Freyd, 1987) and luminance change (Brehaut & Tipper, 1996; Favretto & Hubbard, 2000). The most thoroughly investigated transformation, however, has been that of an object changing spatial location. A number of factors have been found to influence the magnitude of the forward memory shift for objects undergoing implied movement. The size of the shift was shown to be linearly related to the implied speed of the object in the inducing display (Freyd & Finke, 1985), and in an acceleration situation, the magnitude of the shift was sensitive to the final velocity, not just the average velocity (Finke, Freyd, & Shyi, 1986). Thus, the magnitude of the shift varies with the spatio-temporal parameters of the object.

In addition to reflecting the immediate dynamic history of an object, the memory shift can also reflect anticipated behaviours of an object. For example, if observers view an object whose motion changes direction at predictable points, the forward memory shift at the point of expected direction change will be reduced, apparently reflecting the anticipated deceleration associated with the direction change (Hubbard & Bharucha, 1988; Verfaillie & d'Ydewalle, 1991; see Kerzel, this issue, for additional findings related to predictability). Representational momentum shifts also reflect expectations about object behaviour that are derived from semantic knowledge associated with the identity of the object. For example, Reed and Vinson (1996) have shown that for two identically appearing objects, one identified as a rocket can have a larger forward memory shift than one identified as a church steeple (see also Vinson & Reed, this issue). Similarly, a bird flying forward can have a larger shift than a bird flying backward (Freyd & Miller, 1993).

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Evidence from RM experiments, then, indicates that observers of a moving object represent ongoing kinematic information about the object and also expectations about likely behaviour, drawn either from recent experience or from conceptual information. While there has been much research investigating which properties of the object and of the trajectory influence the represented dynamics, there has been little work on how the attentional state of the observer affects the RM shift. Is attention required to establish or draw upon these representations? The purpose of the following experiments is to examine how the representation of dynamic events changes when the observer experiences a heavier attentional load. Experiment 1 tests the effect on RM when the observer must pay attention to two dynamic objects rather than just one. In Experiment 2, the observer must attend to a single dynamic object while simultaneously performing a distracting secondary task.

BACKGROUND RESEARCH

In the typical RM study, only one object in the inducing display is dynamic. However, there have been a few studies in which RM was tested when multiple dynamic objects were present in the display. Finke and Freyd (1985) presented an inducing display in which three dots moved in independent directions over three discrete appearances, and observers attempted to remember the final configuration of the three dots. Memory was probed with configurations that either matched the final positions of the dots, or that depicted the three dots as moving forward or backward along their trajectories. Observers tended to endorse probe configurations that were consistent with continued motion of the dots, which suggests that RM does occur when observers are attempting to spread their attention across multiple objects. However, the possibility that observers adopted a strategy of attending to only one of the dots in the inducing display and probe configuration, rather than spreading attention across the three dots, cannot be ruled out.

Brehaut (1989) examined the effect of flanking distractors on the RM shift associated with a central stimulus and found that the memory shift for an attended central stimulus undergoing implied rotation was unaffected by the presence of dynamic distractors. In contrast, Whitney and Cavanagh (this issue) report an effect of dynamic distractors on memory for the position of smoothly translating objects. These experiments did not, however, examine how the situation of focused attention in the presence of dynamic distractors contrasts with divided attention across multiple objects.

Hayes and Freyd (1995) compared the RM memory shift for two conditions, one in which two objects were present, either of which could be probed, and a second condition in which only one object was present in the inducing display. In the two-object condition, two small dots moved in an implied motion sequence, one dot moving on a vertical path and the other moving horizontally. The two dots either moved toward each other or away from each other, a between-subjects factor (Figure 1). The observers' task was to remember the final positions of both dots. Because it was uncertain which dot would be probed, observers were instructed to spread their attention across both objects. Memory was tested by a probe dot that appeared either in the final position of one of the dots, or forward or backwards from this final position along the path of motion (Figure 1). This two-object condition was contrasted with single-object conditions in which, in separate blocks, either the horizontally moving dot or the vertically moving dot from the two-object condition was presented alone.

The two-object condition produced significantly larger forward memory shifts than the single-object conditions, and this was true whether the two objects approached or moved away from each other (Hayes & Freyd, 1995). This finding suggests that when less attention is paid to an object, the forward memory bias associated with the object's implied dynamics becomes larger. However, a possible alternative explanation is that the effect is instead due to

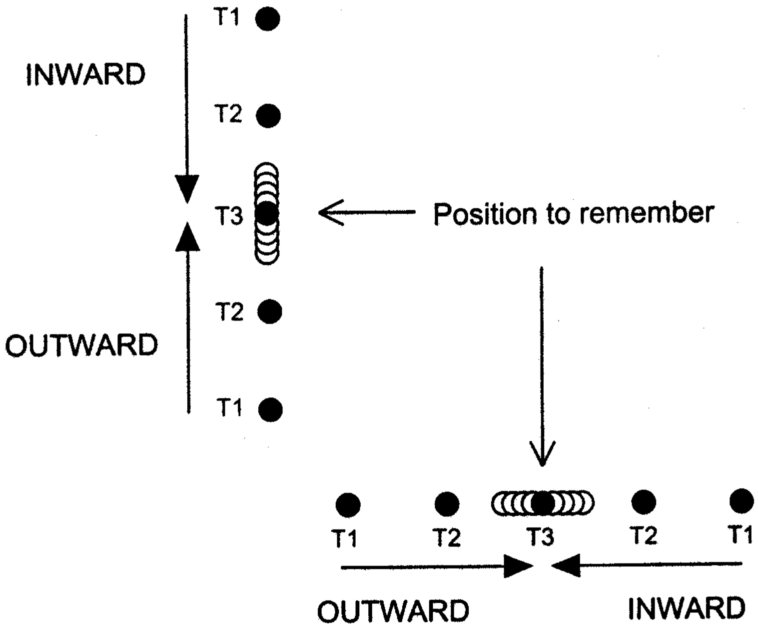

Figure 1. Schematic of the inducing displays for the two-object conditions from Hayes and Freyd (1995). Inward vs. outward motion was a between-subjects factor. T1, T2, T3 refer to time 1, 2, and 3; hence, only two dots appeared at one time. Dots appeared for 250 ms and interstimulus interval was 250 ms; each dot travelled 0.5 degrees visual angle between presentations. Probe positions are depicted as unfilled dots.

the different perceptual configurations that arise when two dots are present compared to when a single dot is present. Experiment 1 builds on the finding of Hayes and Freyd (1995) and provides more direct evidence for a role of attention. In all conditions two objects are present, and attention is manipulated by varying the probability that one or the other object will be probed. Thus the perceptual configuration remains the same as attention is manipulated.

EXPERIMENT 1

In this experiment, observers viewed two objects that each changed across three successive presentations. Above fixation a dot translated horizontally across the screen, either rightward or leftward (a between-subjects factor). Below fixation a square either grew or shrank in size (also a between-subjects factor). Observers attempted to remember both the final position of the dot and the final size of the square. Attention was manipulated by varying the probability that one or the other object was probed. In three separate blocks the two objects could be probed equally often, in a 35% to 65% ratio, or in a 20% to 80% ratio. Based on the findings from Hayes and Freyd (1995), the predicted result was that in the low attention conditions when an object is probed only 20% or 35% of the time, the forward memory shift would be larger than in the high attention conditions when an object is probed 65% or 80% of the time.

Experiment 1 extends the design of Hayes and Freyd (1995) in two ways. As already mentioned, in this experiment the low attention displays and the high attention displays are perceptually identical; thus, an effect of the attention manipulation cannot be attributed to differences in configural properties of the displays. Second, testing memory for the size change of an object allows us to test the effect of attention for a transformation other than translation in the picture plane.

Method

Participants

Forty-eight undergraduate students at the University of Oregon participated. All participants gave informed consent and received partial course credit in a psychology course for their participation.

Stimuli and apparatus

The experiment was conducted in a dimly lit room. Stimuli were presented on a Macintosh colour monitor using a Macintosh IIci computer. Screen resolution was 640 by 480 pixels and refresh rate was 66.7 Hz. Stimulus presentation and response collection were controlled by a custom written computer

program. Participants sat approximately 80 cm from the computer screen. Stimuli were displayed on a black background.

Each trial consisted of an inducing display and a probe image. The inducing display consisted of three discrete presentations of a fixation cross located slightly above the centre point of the screen, a green dot that appeared above fixation, and a red square that appeared below fixation. Across the three successive presentations, the dot moved from the periphery to the centre of the screen, and the square either shrank or grew in size (Figure 2.) A fixation cross was included to encourage participants to spread attention across the entire display, and to prevent participants from lapsing into a strategy of fixating the more frequently probed object. Each of the three displays had a duration of 250 ms, and interstimulus intervals were 250 ms.

The dot moved horizontally along a path located 1.3 degrees visual angle above fixation. The first appearance of the dot was located 1.9 degrees visual angle to the left or right of the midline of the screen, a between-subjects factor. The second appearance was located midway between the first and third dot, which was located on the midline. The dot diameter subtended 0.34 degrees visual angle.

The square was centered at a point 2.8 degrees visual angle below fixation. In the shrink condition, the first presentation of the square had side lengths of

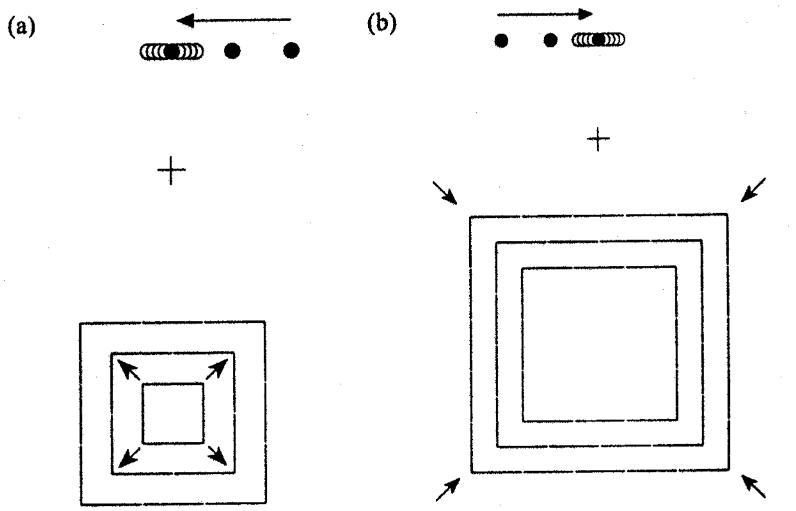

Figure 2. Depiction of two of the four display types for Experiment 1 (not shown are leftward dot with shrinking square and rightward dot with growing square). All three images of the inducing displays are shown here collapsed into a single image, with arrow directions indicating direction of transformation. For the dot, probe positions are shown as outline dots; probe positions for the square are not depicted. (a) Leftward dot movement with growing square. (b) Rightward dot movement with shrinking square.

3.7 degrees visual angle. Across successive appearances, the sides of the square shortened in increments of 0.7 degrees. In the grow condition the initial appearance of the square had side lengths of 0.8 degrees, and across successive appearances the sides of the square lengthened by 0.7 degrees. For both the shrink and grow conditions the third appearance of the square had side lengths of 2.2 degrees visual angle.

Participants attempted to remember both the location of the third appearance of the dot, termed the target dot, and the size of the third appearance of the square, the target square. After a 250 ms retention interval, a probe stimulus appeared that probed memory for one of the objects. When memory for the dot was tested, the probe was identical in form to the target dot and could be located in the exact location of the target dot, or in one of eight distractor positions located along the line of motion. Distractor positions were symmetrically distributed about the target position at 3 pixel intervals. The entire range of distractor positions subtended 0.4 degrees visual angle. When memory for the square was tested, the probe could be the same size as the target square or one of eight distractor sizes. Four distractor sizes had side lengths larger than the target square by increments of 3 pixels, and four distractor sizes had side lengths that were smaller than the target square by 3 pixel increments. The largest probe square side subtended 2.5 degrees visual angle; the smallest probe square side subtended 1.9 degrees.

The probe dot or square remained on the screen until participants responded; response keys were the "s" and "l" keys on the computer keyboard, respectively labelled "S" for "same" and "D" for "different". Participants initiated the next trial by pressing the space bar after a tone indicated that the computer program was ready to generate another trial.

Design

Participants completed three blocks. Each block consisted of 126 trials (9 probe positions × 14 repeats) presented in a random order. In each block, for a given target each probe position was repeated equally often. The probability that a target was probed was manipulated by varying the ratio of repeats per probe position for the two targets. In one block, called the 50% condition, both targets were probed equally often, i.e., seven repeats per probe position per target. In a second block, one target was probed 45 out of 126 times, or close to 35% of the time; the other target was probed the remaining 65% of the time. Thus, for the 35% target there were five repeats per probe position and for the 65% target there were nine repeats per probe position. In the third block, the target that was probed 35% of the time in the 35–65% block was probed only 27 out of 126 times, or nearly 20% of the time; the other target was probed 80% of the time. Repeats per probe position were three for the 20% target and eleven for the 80% target. Over all three blocks, then, one target was probed 35% of the time and is referred to as the "less attended object" and one object was probed 65% of the time and is referred to as the "more-attended object".

The attention manipulation, therefore, consists of a comparison of six conditions, the three "less-attended object" conditions, called the low attention conditions, and the three "more-attended object" conditions, called the high attention conditions. Within the high and low attention conditions, there are three probability levels, a neutral level (the 50–50% conditions), a medium probability difference (the 35% and 65% conditions), and an extreme probability difference (the 20% and 80% conditions). In the 50–50% conditions, both the objects were probed equally often; however, one of the objects is the less-attended object when the other two blocks are also considered. Similarly, the other object is the more-attended in the three block context. These two 50% conditions are distinguished by the labels "50%-low attention" and "50%-high attention".

For half the participants the dot was the more attended object, and for the other half the square was more attended. Within these two groups, rightward vs. leftward dot motion, growing vs. shrinking square, and block order were completely counterbalanced.

Procedure

The experimenter read aloud instructions that emphasized both speed and accuracy, but accuracy was encouraged over speed. Participants were told that the number of same and different responses might not be equal, but they were not informed about the actual proportion of same responses. Participants were instructed to divide their attention across both objects and they were not given any information regarding the target probability manipulation. A set of nine practice trials preceded each block. Participants were free to take breaks at any time during the experiment.

Results

Response distributions for the two transformations, translation and size change, were analysed separately. Distributions of same responses as a function of probe position are shown separately for the dot and the square in Figure 3. Data are collapsed across participants and direction of dot movement or direction of size change. Positive probe positions are those that are further along from the target position in the direction of continued transformation. Probe position zero represents the probe position identical to the target position. If memory were not biased, then the central tendency of the distribution of same responses would be zero. It is clear from Figure 3 that the response distributions are biased in the forward direction of continued transformation.

Two characterizations of the distributions are of interest, the central tendency and the variability. The central tendency represents the remembered

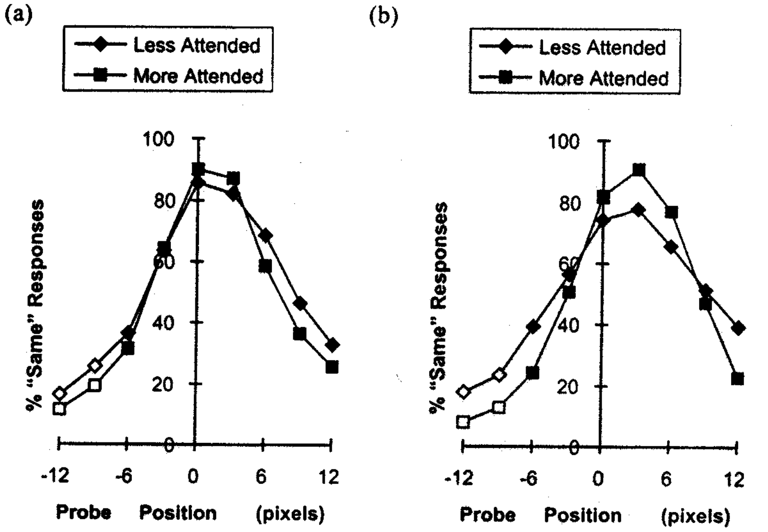

Figure 3. Percent same responses as a function of probe position for responses to (a) the dot and (b) the square in Experiment 1. Attention is a between-subjects factor; less attended conditions include 20%, 35%, and 50% probe probabilities and more attended include 50%, 65%, and 80% probe probabilities. Data points with outline form indicate probe positions that were excluded from the corrected weighted means calculations.

position of the target, and is the measure of memory shift. The variability of the distribution, the measure of the precision of the responses about the central tendency, is of interest as a measure of attention. Previous research has indicated that under dual task conditions, a number of perceptual judgements, such as perception of colour, orientation, and location, become less precise (Prinzmetal, Amiri, Allen, & Edwards, 1998; Prinzmetal, Nwachuku, & Bodanski, 1997; Prinzmetal & Wilson, 1997). Therefore, it might be expected that when less attention is available for judging the final location of the dynamic object, the distribution of same responses will cluster less tightly about the central tendency, and this increased variance would be an indication that the attention manipulation has been effective.

Assessment of central tendency. Central tendency was estimated by calculating the mean probe position endorsed as "same" for each condition for each participant. For this calculation each same response is weighted by the probe position value at which it occurred, and the average of these weighted same responses is termed the weighted mean.

When designing the range of probe positions, an effort is made to select probe positions that will capture the entire distribution of responses. However, because of the RM forward memory bias, it is typically difficult to capture the distribution of responses for forward positions as completely as for backward positions, causing the distribution of same responses to be negatively skewed. The effect of the negative skew becomes more severe as the forward shift becomes larger. To reduce the effect of the unbalanced tails on the weighted mean, a "corrected" weighted mean is calculated, which excludes probe positions that received fewer than 20% same responses when all conditions are averaged across all participants (Faust, 1990). In both Experiments 1 and 2 it is this corrected weighted mean that is the estimate of the central tendency used in statistical analyses of the memory shifts.

As can be seen in Figure 3, the distributions of same responses for both the dot and the square are negatively skewed for both the high and low attention conditions because the range of distractor probes in the positive direction was not sufficient to capture the entire distribution symmetrically. Eliminating from analysis all probe positions that did not receive at least 20% same responses, removes, in this case, the two most negative probe positions, and the distributions for all four conditions become nearly symmetrical.

Assessment of variability. The precision associated with the distribution of same responses was estimated by calculating the average absolute deviation score for each participant. For each condition, the absolute deviation of each same response from that participant's corrected weighted mean was calculated, and these absolute deviations were summed and divided by the total number of same responses. Following Prinzmetal and Wilson (1997), this measure of variability was used because it is more robust to violations of assumptions of analysis of variance than is the standard deviation (Keppel, 1991, p. 102).

Results for the dot. The summary data for the corrected weighted means for responses to the dot are shown in Table 1. The corrected weighted means are

TABLE 1

Mean estimated memory shifts (pixels) and standard error for dot position (collapsed across direction of motion), and for size of shrinking and growing squares as a function of high and low attention conditions, Experiment 1

	Probe probability					
	High attention			*Low attention*		
Stimulus	*80%*	*65%*	*50%*	*50%*	*35%*	*20%*
Dot	1.93	1.98	2.12	2.32	2.67	2.64
	(0.23)	(0.23)	(0.28)	(0.23)	(0.26)	(0.35)
Shrinking square	2.84	3.09	3.09	4.60	5.03	3.77
	(0.30)	(0.30)	(0.34)	(0.37)	(0.67)	(0.56)
Growing square	2.68	2.53	2.77	1.17	1.15	1.43
	(0.30)	(0.33)	(0.32)	(0.42)	(0.49)	(0.59)

based on probe positions "–6" to "+12", according to the 20% same response criterion discussed earlier. The pattern of corrected weighted means suggests that as the dot is probed less frequently, which presumably decreases attention paid to the dot, the forward memory shift increases.

The corrected weighted means scores were subjected to an ANOVA with three between-subjects factors, attention (high vs. low), dot movement (leftward vs. rightward), and square movement (i.e., whether the type of size transformation of the square, shrinking vs. growing, affected memory for the dot); and one within-subjects factor, level of probability manipulation—extreme (20% or 80%), medium (35% or 65%), or neutral (50%). There was a marginal effect of high vs. low attention, $F(1, 40) = 3.14, p = .08$, and no other significant effects.

To examine the main effect of attention further, a second ANOVA was performed that excluded data from the 50% conditions, since the 50% conditions would not be expected to differ between the high and low attention conditions. This ANOVA had the same factors as the previous one, but with only two levels of the probability manipulation, the extreme value (20% or 80%) and the medium value (35% or 65%). There was a main effect of attention—mean shifts of 1.96 pixels for high attention vs. 2.66 pixels for low attention; $F(1, 40) = 5.41, p = .025$—which did not interact with any other factor. This result is in accordance with the findings of Hayes and Freyd (1995) that with less attention, memory shift is larger. Other significant effects were a main effect of dot direction, $F(1, 40) = 4.45, p = .04$, with leftward movement producing larger shifts, and a main effect of square direction, $F(1, 40) = 5.41, p = .025$, with shifts for the dot being larger when the square is shrinking than when it is growing. Finally, there was a significant interaction between square direction and probability manipulation; the effect on dot movement of whether the square was shrinking or growing was greater at the extreme probabilities (20% and 80%) than at the medium probabilities (35% and 65%), $F(1, 40) = 8.84, p = .005$.

To examine whether the distribution of responses became more variable with less attention, average absolute deviation scores were calculated for each condition for each individual (Table 2). An ANOVA with the same factors as the previous analysis of the corrected weighted means was conducted. Low attention conditions were significantly more variable than the high attention conditions: 4.05 vs. 3.64 pixels; $F(1, 40) = 5.46, p = .02$. There was a main effect of square direction, with responses to the dot being less variable when the square was growing: 4.04 vs. 3.64 pixels; $F(1, 40) = 5.10, p = .03$. Attention and square direction interacted, $F(1, 40) = 5.12, p = .03$, such that the variability in dot responses was particularly low for the high attention grow condition. A second ANOVA that excluded the 50% probability conditions produced the same pattern of significant results.

To summarize the analysis of the dot responses, forward memory shifts were larger in the low attention conditions (probability conditions 20% and 35%) than in the high attention conditions (probability conditions 65% and 80%). Analysis of the average absolute deviation scores indicates that variability was higher in the low attention conditions.

TABLE 2

Mean variability in responses (pixels) and standard error for the dot (collapsed across direction of motion), and for shrinking and growing squares as a function of high and low attention conditions, Experiment 1

	Probe probability					
	High attention			*Low attention*		
Stimulus	*80%*	*65%*	*50%*	*50%*	*35%*	*20%*
Dot	3.55 (0.16)	3.52 (0.18)	3.84 (0.18)	4.11 (0.10)	4.10 (0.17)	3.95 (0.16)
Shrinking square	3.83 (0.14)	3.98 (0.18)	3.93 (0.20)	3.70 (0.20)	3.65 (0.22)	4.20 (0.21)
Growing square	3.18 (0.25)	3.56 (0.21)	3.40 (0.19)	3.78 (0.26)	3.84 (0.23)	4.23 (0.24)

Results for the square. The summary data for the corrected weighted means for responses to the square are shown in Table 1. The corrected weighted means (based on positions "–6" to "+12") were analysed in the same fashion as for the dot responses. An ANOVA with between-subjects factors of attention (high vs. low), square movement (shrinking vs. growing), and dot movement (i.e., whether the direction of dot movement, rightward or leftward, affected memory for the square); and a within-subjects factor of level of probability manipulation (extreme: 80% or 20%; medium: 35% or 65%; neutral: 50%) revealed no main effect of attention, $F(1, 40) = 0.00, p = 0.95$. There was, however, a significant main effect of square direction, $F(1, 40) = 21.54, p = .0001$, and an interaction between square direction and attention, $F(1, 40) = 13.96, p = .0006$. Overall the shrinking condition produced larger forward shifts than the growing condition (mean shifts of 3.74 vs. 1.96 pixels). The nature of the interaction between attention and square direction is clear in Table 1. The high attention conditions are roughly equal for the growing and shrinking square conditions, but when attention is diminished, forward shifts increase in the shrink condition but forward shifts decrease in the grow condition. This suggests that when attention is diminished, there is an increased tendency to endorse smaller probes. Finally, there was an interaction between probability manipulation and square direction, $F(2, 80) = 3.64, p = 0.03$, probably largely due to the large forward shift in the 35% condition for the shrinking square. A second ANOVA was conducted that excluded the 50% conditions, and it produced the same pattern of significant results.

The effect of attention on the variability of responses to the square was tested by subjecting the average absolute deviation scores to an ANOVA with the same factors as that for the corrected weighted means. There was no significant main effect of attention, $F(1, 40) = 1.87, p = .17$, although the means are in the expected direction (3.65 pixels for high attention, 3.90 pixels for low attention, see Table 2). There was however a significant interaction between attention and probability level, $F(2, 80) = 9.32, p = .0002$. The nature of this interaction was that the variability was equivalent in the high and low attention conditions for the neutral and medium level probabilities, but at the extreme probability levels there was greater variability for the low attention condition (4.21 pixels for the 20% condition; 3.51 pixels for the 80% condition). An ANOVA with the same structure that omitted the 50% probability conditions produced the same pattern of significant results.

Discussion

The effect of attention on memory for the dot position is consistent with the results of Hayes and Freyd (1995); the forward memory shift increased when less attention was paid to the object. The effect of diminished attention on memory for the square is clearly different. It appears that the overriding effect of diminished attention to the square is an increased tendency to endorse smaller probes. Hubbard (1996) has shown that when observers view with full attention a static square, they tend to remember the square as being smaller than actual size. The experiment presented here suggests that this bias in memory for size may interact with attention, with the bias becoming stronger as attention is diminished.

EXPERIMENT 2

Experiment 1 showed that the RM shift associated with a translating object increases when attention is divided between that object and a competing object in the visual display. Experiment 2 was designed to examine whether this effect generalizes to situations where attention is distracted not by competing objects, but by a non-visual secondary task.

Method

Participants

Twelve individuals from the Eugene, Oregon community participated in the experiment. All participants gave informed consent and were paid for their participation.

Stimuli and apparatus

Computer apparatus was the same as in Experiment 1. Participants were seated approximately 80 cm from the computer screen. Stimuli were displayed on a black background. No fixation point was provided and participants were free to make eye movements.

Primary task. The participants' task was to remember the final location of a pink dot that moved in three discrete presentations from the periphery to the center of the screen. The dot had a diameter of 4.7 mm, subtending 0.3 degrees of visual angle. The first dot appeared 1.4 degrees visual angle to either the left or right of the centre of the screen, and the second dot appeared midway between the first and the third dot, which appeared at the centre of the screen. Each dot presentation had a duration of 250 ms, and interstimulus intervals were 250 ms. This portion of the display is termed the inducing display. Participants attempted to remember the position of the third dot, the target dot. Following a retention interval of 250 ms a probe image appeared, which was identical in form to the dots in the inducing display and could appear in one of nine positions. One probe position was identical to the position of the target dot, four probe positions were to the right of the target position at 4 pixel intervals, and four were to the left at 4 pixel intervals. The entire range of probe positions spanned 0.8 degrees of visual angle. The probe dot remained on the screen until participants responded by pressing a key for same or different as in Experiment 1. Participants initiated the next trial by pressing the space bar after a tone sounded indicating that the computer program was ready to generate another trial.

Secondary task. In the dual task conditions, a metronome played continuously at a rate of 58 beats per minute. Participants counted aloud in time with the beats of the metronome. In separate blocks, participants counted up to thirty by multiples of one, multiples of two, or multiples of three. When 30 was reached, the participant began again and repeated the procedure continuously until the set of primary task trials was over. It was predicted that counting by ones, twos, and threes would serve as three levels of increasing difficulty of the secondary task and thus provide three levels of increasing distraction.

Design

Each observer participated in the single-task condition, in which the primary task was performed in silence, and in all three dual-task conditions in separate blocks each consisting of 72 trials (9 probe positions × 8 repeats). These four conditions were presented in a different order for each of the 12 participants. The four conditions occurred equally often in the four possible order positions. Half the participants viewed the dot moving rightward and half leftward.

Procedure

Instructions for the primary task emphasized both speed and accuracy, but accuracy was emphasized over speed. Participants were told that the number of same and different responses might not be equal, but they were not informed about the actual proportion of same responses. For the dual task conditions participants were encouraged to consider the two tasks equally important. Participants were informed that the experimenter would be keeping track of how many times they counted to 30; this was done to encourage the participants to count without interruption through the entire range of numbers. Each block was preceded by nine practice trials.

Results

Secondary task. All 12 participants performed satisfactorily on the secondary task. Although errors such as producing a wrong number, becoming lost in the number series, and missing beats, were common, the errors did not appear to be related to the point at which the participant was in the primary task trial. Two individuals lagged behind the beat of the metronome but did so consistently throughout the entire range of counting and in all three divided attention conditions. Ten individuals were able to keep time well, producing a number more or less in time with the metronome.

Primary task. Distributions of same responses as a function of probe position are shown in Figure 4. Data for all four conditions are shown, collapsed across participants and direction of dot movement. For all conditions, positive probe positions are those that are further along from the target position in the direction that the dot was moving. It is clear from Figure 4 that in all conditions the response distributions are biased in the forward direction of motion.

The summary of the central tendency data are shown in Table 3. The corrected weighted means are based on positions "–4" to "+16" according to the 20% same response criterion adopted in Experiment 1. A preliminary analysis of variance on the corrected weighted means scores for individual participants revealed no significant main effect or interactions involving the between-subjects variable of left vs. right direction of dot movement, and this factor was therefore dropped from subsequent analyses.

An analysis of variance performed on the corrected weighted mean scores revealed a significant effect of condition, $F(3, 69) = 5.27$, $p = .004$. It is clear from Table 3 that the divided attention conditions produced a larger memory shift, and the contrast comparing the single task condition with the combination of the dual task conditions was indeed significant, $F(1, 69) = 12.58$, $p < .01$. The manipulation of the difficulty of the secondary task did not produce differences in memory shifts; there were no significant differences among the corrected weighted means for the three counting conditions.

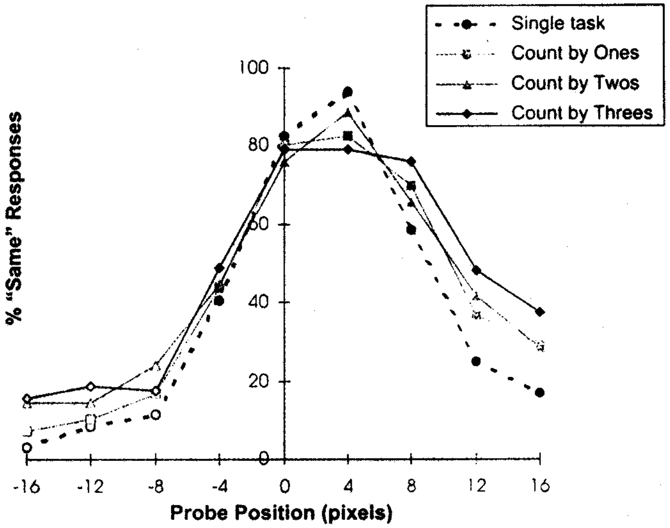

Figure 4. Percent same responses as a function of probe position for the single task condition and the three counting conditions in Experiment 2. Unfilled data points indicate those probe positions that were excluded from the corrected weighted means calculations.

As in previous experiments, the dual task conditions were more variable than the single task condition. As in Experiment 1, the average absolute deviation score was calculated for each participant's distribution of same responses. The dual task conditions showed higher variance (Table 3), and an ANOVA revealed that this effect was significant: $F(3, 69) = 10.13$, $p < .0001$; the contrast comparing the single task condition with the three dual task conditions combined was significant, $F(1, 69) = 23.86$, $p < .01$. Among the dual task conditions, counting by threes produced higher deviation scores than counting by twos, $F(1, 69) = 6.08$, $p < .05$, and no other pairs differed.

TABLE 3
Mean estimated memory shifts (pixels) and mean variability in responses (pixels) with standard errors for the dot as a function of attention conditions, Experiment 2

		Divided attention Multiples for counting task		
	Focused attention	*Ones*	*Two*	*Threes*
Mean memory shift	3.80	4.61	4.62	5.14
	(0.39)	(0.35)	(0.43)	(0.25)
Mean variability	4.05	4.66	4.54	4.96
	(0.24)	(0.17)	(0.22)	(0.18)

Discussion

The distribution of same responses clearly was affected by the addition of a non-visual secondary task. Dual task conditions caused a larger forward memory shift and less precision in the response distributions than the single task condition. To determine whether this effect of the secondary task might be due solely to the presence of the metronome rather than the attention manipulation, a follow-up experiment was conducted in which the metronome played during the full attention condition, but participants were instructed to ignore it. The forward memory shift in that condition did not differ from a full attention condition performed in silence (Hayes, 1997).

GENERAL DISCUSSION

The representational momentum memory shift can be taken as an index of the dynamic information associated with an object at the time memory is probed. The experiments presented here were designed to examine whether attention affects the magnitude of the RM shift. These experiments demonstrated that when attention was diminished, memory for target location for translating objects became more biased toward the direction of continued motion. This increased forward bias occurred whether attention was distracted by competing objects or by a competing task. Additionally, these experiments demonstrated that, as expected, with less attention, localization of dynamic targets became more variable. This result is consistent with the findings of Prinzmetal and colleagues that for a number of perceptual judgements, including spatial location judgements, the primary effect of diminishing attention is that the responses become less precise (Prinzmetal et al., 1997, 1998).

In contrast, when the object transformation was a square changing size (Experiment 1), diminished attention caused an increase in the forward RM shift only when the square was shrinking in size. When the square grew in size, memory for the final size was still in the forward direction of continued size increase, but with less attention this forward shift became smaller. The forward RM shift is apparently counteracted by a backward memory shift. Hubbard (1996) has shown that when viewers attempt with full attention to remember static squares, there is a bias to misremember the square as being smaller. Our results from Experiment 1 suggest that this bias becomes stronger with diminished attention.

It may be that there is a general tendency for perceptual biases to increase when attention is diminished. Prinzmetal et al. (1998) discovered that memory for some colours tended to be biased, and when attention was diminished this bias also became more pronounced. However, we would not expect that under all circumstances the RM shift will increase when attention is diminished. Rather, we expect that the memory shift will increase under distraction conditions only when focal attention serves to minimize the representation of continued motion. In contrast, we would expect distracting conditions to *decrease* the forward memory shift for situations in which attention is serving to heighten the representation of continued motion, or if attention facilitates the "animation" of an object under consideration.

In the present experiments, the visual event was simply the translation of a dot with uniform speed to a predictable stopping point. The increase in forward memory shift suggests that even when attention is distracted this simple forward motion can be represented. It also suggests that with diminished attention it becomes more difficult to effectively represent the dot's stopping point, even though the stopping point is highly predictable. To use the physical analogy introduced by Finke et al. (1986), applying the cognitive resistance that halts the represented dynamics requires attention.

More generally, attention may be necessary not only for applying the "brakes" to the dynamics of a representation, but for representing any type of change in a dynamic event, be it starting, stopping, or changing speed or direction. Perhaps without attention, the dynamic "*status quo*" continues to be represented, and attention is required to override the *status quo*, even when the change is highly predictable as in our experiments. This proposal can be tested by adapting an experiment by Verfaillie and d'Ydewalle (1991). They demonstrated that when viewers expected a stimulus to accelerate, the forward memory shift at the expected acceleration point was larger than for an identical inducing display in which no acceleration was expected. If these displays were tested under conditions of divided attention, our prediction would be that the expected increase in velocity would be difficult to represent without attention, and that in contrast with the experiments reported here, with less attention the memory shift would be smaller.

We can also consider how attention might modulate the RM effects that involve object identity, such as the finding that a rocket can have a larger forward shift than a chapel steeple (Reed & Vinson, 1996) or that a static image with implied motion, such as a cartoon of a man tilting forward, can show a memory shift in the direction of implied motion (McKeown, 1996). One proposed role of attention is that it serves to bind features together into objects, which allows for access to semantic networks that store knowledge about previously experienced objects, including knowledge about the likely behaviour of the object (Kahneman, Treisman, & Gibbs, 1992). Similarly, Cavanagh and colleagues have proposed that attention mediates access to "sprites", or animation information associated with familiar objects (Cavanagh, Labianca, & Thornton, 2001). We propose that such attentional mechanisms are probably also necessary for object identity to affect the RM memory shift. We would expect that when attention is distracted, the RM shift will reflect certain spatiotemporal parameters of the trajectory, but that differences in the memory shift between objects of different identity will disappear. Similarly, we predict that static images that have implied motion will remain stationary without attention.

To summarize, we have found that when attention is distracted from an object undergoing simple, predictable translation in space, the RM memory shift increases. This indicates that under distraction, such motion is represented, but the stopping point is less effectively represented. We propose that, more generally, object dynamics can be represented when attention is diminished, but that representing a *change* in the dynamics requires attention, even when the change is highly predictable. We also suggest that object identity will not affect the RM shift without attention. These proposals indicate future directions for investigations into the nature of the interaction between attention and dynamic representations.

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