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Displacement in depth: Representational momentum and boundary extension

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Abstract Memory for targets moving in depth and for stationary targets was examined in five experiments. Memory for targets moving in depth was displaced behind the target with slower target velocities (longer ISIs and retention intervals) and beyond the target with faster target velocities (shorter ISIs and retention intervals), and the overall magnitude of forward displacement for motion in depth was less than the overall magnitude of forward displacement for motion in the picture plane. Memory for stationary targets was initially displaced away from the observer, but memory for smaller stationary targets was subsequently displaced toward the observer and memory for larger stationary targets was subsequently displaced away from the observer; memory for the top or bottom edge of a stationary target was displaced inside the target perimeter. The data are consistent with Freyd and Johnson's (1987) two-component model of the time course of representational momentum and with Intraub et al.'s (1992) two-component model of boundary extension.

Introduction

When observers are asked to indicate the remembered final location or orientation of a previously perceived moving target, they often indicate a location or orientation that is slightly beyond the target's true final location or orientation. This displacement or shift between the true final position and the remembered final position has been referred to as *representational momentum* (Freyd & Finke, 1984; for review, see Hubbard, 1995c). Although much has been learned about representational momentum, the bulk of our knowledge comes from studies that have employed stimuli that undergo either rotation or translation in the picture plane. The existence of differences in representational momentum for targets moving in the picture plane and for targets moving in depth has not been empirically examined, and so it is not known whether the representation of a target that undergoes motion in depth exhibits displacement along the path of anticipated future target motion, similar to the displacement exhibited by the representation of a target that undergoes rotation or translation in the picture plane.

Kelly and Freyd (1987) pointed out that the laws of physical momentum apply equally well to targets moving in depth and to targets moving in the picture plane. On this basis we might predict that memory for targets moving in depth should exhibit representational momentum. However, there is also a theoretical reason for predicting that the magnitude of representational momentum for targets moving in depth should be less than the magnitude of representational momentum for targets moving in the picture plane; namely, a movement in depth would not change the two-dimensional retinal coordinates of the target as much as an equivalent movement in the picture plane would. As is illustrated in Figure 1, the magnitude of change in two-dimensional retinal coordinates for targets moving the same objective distance is a function of how close the path of target motion is to the picture plane, such that paths more parallel to the picture plane produce greater magnitudes of change in retinal coordinates. If memories for the spatial coordinates of targets that move in different directions are displaced in the direction of motion by the same absolute amount (in three-dimensional environmental coordinates), then the absolute magnitude of forward displacement from the observer's point of view (in two-dimensional retinal coordinates) increases as the path of motion gradually changes from orthogonal to parallel to the picture plane. Thus, with other factors held equal, we might not expect as much representational momentum for targets

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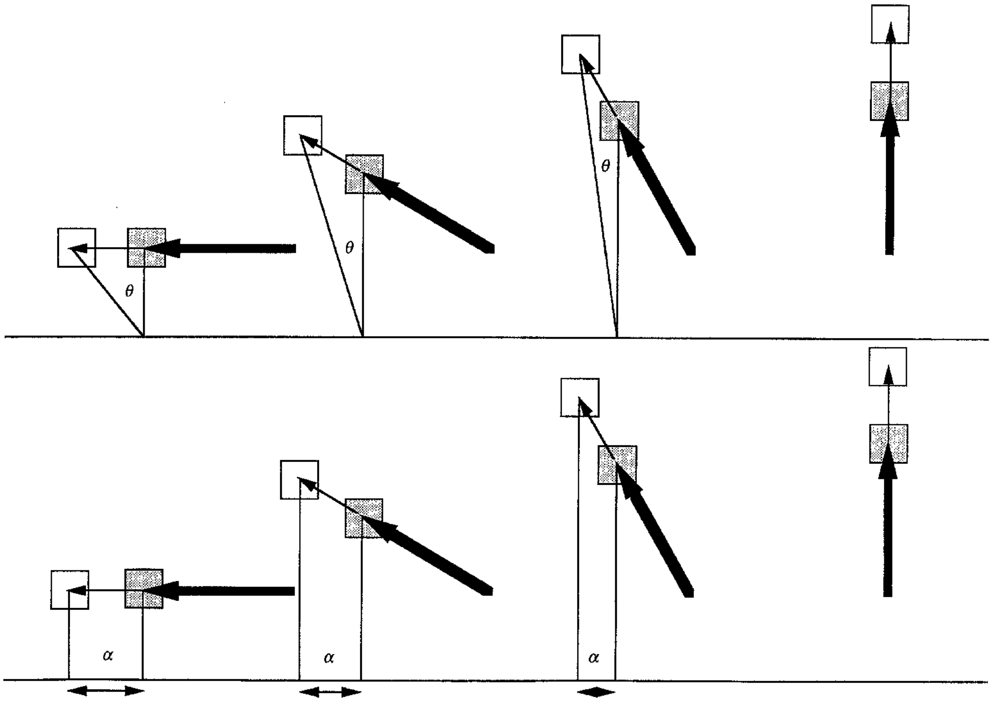

Fig. 1 Examples of the visual angle and picture-plane projection of the magnitude of displacement as a function of the direction of target motion in relation to the picture plane. In both panels the light gray squares indicate the true vanishing point of the target and the white squares indicate the remembered vanishing point. The heavy dark arrows represent the direction of target motion and the light arrows reflect the displacement in judged position along the axis of motion. The picture plane is indicated by a horizontal line. In all examples the target travels an equal distance and the judged vanishing point is displaced in the direction of target motion an equal amount. What differs among the different examples in each panel, however, the direction of travel relative to the picture plane and the resulting visual angle and picture-plane projection of the forward displacement. The examples in the upper panel show how visual angle (θ) of a given displacement changes as a function of the direction of target motion, and examples in the lower panel show how the picture-plane projection (α) of a given displacement changes as a function of the direction of target motion

moving in depth as we do for targets moving in the picture plane.[1]

The case for possible differences between the magnitudes of representational momentum for targets that move in depth and targets that move in the picture plane may also be strengthened if we consider that differences in the magnitude of representational momentum may be found as a function of the direction of target motion within the picture plane. Although the original reports of representational momentum (e.g., Freyd & Finke, 1984, 1985) did not report any differences in the magnitude of forward displacement as a function of the direction of rotation, Hubbard and Bharucha (1988; Hubbard, 1990) reported that horizontal motion led to larger magnitudes of forward displacement than did vertical motion. Halpern and Kelly (1993) subsequently reported that the magnitude of forward displacement exhibited by targets moving toward the right was greater than the magnitude of forward displacement exhibited by targets moving toward the left (in right-handed observers). Given that the magnitude of representational momentum exhibits effects of direction for motion within the picture plane, it may not be as surprising to find differences in the magnitude of representational momentum between motion in the picture plane and motion in depth.

Representational momentum has been characterized as providing evidence of a dynamic aspect of mental representation (Freyd, 1987), the spatiotemporal coherence between the represented and representing worlds (Freyd, 1992, 1993), and the internalization of environmental invariants into our system of representation (Hubbard, 1995b, 1995c, in press). All of

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[1] The appeal to differences in viewer-centered two-dimensional retinal coordinates as a function of the direction of target motion is not meant to imply that representational momentum and related forms of displacement are low-level perceptual phenomena. As Hubbard and Bharucha (1988) discussed, it is quite reasonable that eye movements may contribute to the displacement process, but displacement cannot be a purely low-level perceptual process because the magnitude and direction of displacement are penetrable to higher-order cognitive expectations (see also Hubbard, 1995c). Even if eye movements do not cause representational momentum, changes in the optical flow patterns might nonetheless constrain representational momentum.

these characterizations appeal to both dynamic aspects of memory and to internalizations of observers' expectations regarding the behavior of objects in the world. Even though representational momentum occurring for target stimuli moving in depth has not been empirically examined, it would be useful to examine whether there are any other types of systematic displacements that have been found along the depth axis (i.e., along the line of sight) and whether these displacements may also be characterized as involving both dynamic aspects of memory and internalizations of expectations regarding target behavior.

One type of displacement in depth recently reported that appears to reflect both dynamic aspects of behavior and internalizations of expectations about the world has been reported by Intraub and her colleagues (e.g., Intraub, Bender & Mangels, 1992; Intraub & Bodamer, 1993; Intraub & Richardson, 1989) and is called *boundary extension.* Studies of boundary extension typically show observers a picture of a scene, remove the picture, and after some interval of time show the observers a second picture and ask whether the second picture is the same as the first picture. If the first and second pictures portray the same overall scene, but differ in the visual angles subsumed by the objects in the scene (i.e., the portrayed distance), then the observers are more likely to identify the second picture erroneously as being the same as the first picture if the second picture uses a wider (i.e., more panoramic) camera angle than if the second picture uses a narrower (i.e., more close-up) camera angle than the first picture (Intraub et al., 1992). That is, observers are more likely to extend the boundaries of the picture they remember than to contract the boundaries. Similarly, when observers attempt to draw the first picture from memory, they include elements in their drawings that logically might have been present just beyond the boundaries of the picture, and when later shown the first picture, they may claim that it is "closer up" than before (Intraub & Richardson, 1989).

If the perimeter length of a picture is held constant, then incorporation of any additional material within the pictorial boundaries would seem to require that at least some of the pictorial elements should be remembered as slightly smaller than those elements were initially perceived to be. In other words, the visual angle of each pictorial element when that element is remembered, will be slightly smaller than the visual angle of that element when that element was first perceived. This decrease in the size of the remembered visual angle is necessary in order to prevent any overlap or occlusion of either the original pictorial elements or the newly incorporated material. Remembering the target as slightly smaller or as occupying a slightly smaller visual angle is geometrically equivalent to a displacement of the target away from the observer. Boundary extension may therefore be considered to reflect a simultaneous displacement of the stationary elements within the picture, although the extent to which different figural elements may be displaced to differing degrees, or the extent to which figural elements may be displaced more or less than background elements, has not been explicitly addressed in the literature. Even so, we may consider boundary extension to reflect displacement of an entire scene, whereas representational momentum has generally been considered to reflect displacement of just a single figural moving target (but see Finke, Freyd, & Shyi 1986) against a stationary background (but see Hubbard, 1993).

Given that boundary extension is usually assessed with more complex, naturalistic, or ecological stimuli than are usually used in assessing representational momentum (although see Freyd, 1983; Futterweit & Beilin, 1994), it is unclear to what extent we may expect boundary extension to be produced with the relatively impoverished square and rectangular stimuli typically used in experiments on visual representational momentum. If boundary extension is dependent upon complex scene expectations (as is suggested by Intraub & Bodamer, 1993), then we might not expect to see boundary extension if the stimuli are insufficiently complex to evoke scene schemata. However, it is not clear exactly how complex a stimulus must be in order to evoke such schemata, and the pictorial stimuli used in previous studies of boundary extension may have been far more naturalistic, ecological, or complex than was necessary for the evocation of the boundary-extension process.

In the following experiments observers were presented with simple computer-animated square inducing stimuli that portrayed movement in depth. If representational momentum occurs, then when the inducing stimuli appear to approach, the observers should be more likely to accept a probe portrayed as being closer than the final inducing stimulus and less likely to accept a probe portrayed as being further away than the final inducing stimulus, and when the inducing stimuli appear to recede, the observers should be more likely to accept a probe portrayed as being further away than the final inducing stimulus and less likely to accept one as being closer than the final inducing stimulus. Furthermore, the magnitude of forward displacement should increase with increases in target velocity. If boundary extension occurs, then the observers should be more likely to accept a probe portrayed as being slightly further away than one portrayed as being slightly closer, regardless of whether the inducing stimuli appear to approach or recede.

Experiment 1

In this experiment observers were shown an animated sequence of four sequential inducing stimuli followed by a probe stimulus.[2] The inducing stimuli and the probe were square in shape and the centers of each inducing stimulus and the probe were located at the same screen coordinates. Given the two-dimensional nature of the computer screen that displayed the stimuli, changes in depth could not be shown directly, but instead were indicated by changes in the visual angle subsumed by each of the inducing stimuli and the probe. The inducing stimuli were portrayed as either approaching, receding from, or maintaining a constant distance from the observer. The probe was portrayed as either being slightly closer to the observer than the final inducing stimulus, slightly further from the observer than the final inducing stimulus, or at the same distance from the observer as the final inducing stimulus. The observers judged whether the probe was at the same implied distance as the final inducing stimuli.

Method

Participants. The observers were 12 undergraduates at the University of Arizona who participated in return for partial course credit in an introductory psychology course. All participants were naive to the hypotheses until after their data had been collected.

Apparatus. The stimuli were displayed upon and the data collected by an Apple Macintosh SE/30 microcomputer. The microcomputer was approximately 60 cm away from the observers, but the observers could adjust this distance slightly in order to achieve maximum comfort and confidence in their responses.

Stimuli. The inducing stimuli and probe were black outline squares drawn on a white background. The stimuli were centered at the approximate midpoint of the microcomputer screen; they either grew successively larger throughout the inducing sequence (i.e., the approach condition), grew successively smaller throughout the inducing sequence (i.e., the recede condition), or maintained the same size throughout the inducing sequence (i.e., the stationary condition). In the approach condition, the length of each side of each inducing stimulus was either 16, 24, 36, or 54 pixels (approximately 40, 60, 90, or 135 min of visual arc). In the recede condition, the length of each side was either 181, 121, 81, or 54 pixels (approximately 453, 303, 203, or 135 min of visual arc). The sizes of the inducing stimuli in both approach and recede conditions were chosen so that the two-dimensional surface area of each square changed by a factor of 2.25 from the two-dimensional surface area of the preceding inducing stimulus (and the length of each side of the square changed by a factor of 1.5 from the length of each side of the preceding inducing stimulus). In the stationary condition, the length of each side of each inducing stimulus was 54 pixels. Thus, the final inducing stimulus was the same size in all three direction conditions. The probe remained visible until the subject responded. The length of each side of the probe was either 42, 48, 54, 59, or 64 pixels, and these sizes were chosen so that the middle probe was the same size as the final inducing stimulus, the probes adjacent to the middle probe decreases or increased by 20% of the surface area of the final inducing stimulus, and the smallest and largest probes decreased or increased by 40% of the surface area of the final inducing stimulus. Keeping the ratio of change in surface area constant across inducing stimuli and keeping the ratio of surface areas of the different probes constant was also consistent with Intraub and Bodamer (1993) who made the target objects in their probe pictures either 25% larger or 25% smaller than the target objects in the original pictures. The center of the probe was located at the same screen coordinates as the center of each inducing stimulus. Velocity was controlled by manipulation of the duration of each inducing stimulus and the ISI between inducing stimuli. The duration and ISI were 500, 300, and 100 ms for the slow, medium, and fast trials, respectively; the retention interval between the final inducing stimulus and the probe was equal to the stimulus duration and ISI on that trial. Each observer received 180 trials (3 directions × 3 velocities × 5 probes × 2 replications) in a different random order.

Procedure. The observers were first given a practice session consisting of 12 trials, randomly drawn from the experimental trials. Observers were instructed to interpret the displays as depicting an object that remained the same size but was moving in depth, and examples of how the visual angle of an object changes when that object approaches or recedes were given. They began each trial by pressing a designated key, and the first inducing stimulus immediately appeared. After the probe had appeared, the observers judged whether it was at the same implied depth as the final inducing stimulus and pressed a key marked *S* (for same) or a key marked *D* (for different) to indicate their response. Observers then initiated the next trial.

Results and discussion

The choice probabilities are displayed in Figure 2. The *x* axes for the approach and recede conditions have been labeled so that the right side of each *x* axis lists probes beyond the final inducing stimulus and the left side of each *x* axis lists probes behind the final inducing stimulus (i.e., shifts to the right in the distributions of *same* responses indicate displacement in the direction of target motion, and shifts to the left indicate displacements in the direction opposite to target motion). The *x* axis for the stationary condition has been labeled so that the right side of the *x* axis lists probes larger than the final inducing stimulus and the left side of the *x* axis lists probes smaller than the final inducing stimulus (i.e., shifts to the right indicate displacement toward the observer and shifts to the left indicate displacement away from the observer). If observers were responding

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[2] It might be objected that representational momentum could be maximized by presenting a smoothly changing stimulus (i.e., apparent motion) rather than a series of discrete and separated stimuli (i.e., implied motion). However, the majority of studies undertaken by Freyd and her colleagues presented discrete and separated inducing stimuli and reported robust representational momentum (when implied motion was in a consistent direction). Freyd (1993) has speculated that a stimulus exhibiting consistent change along a continuous dimension produces representational momentum regardless of the surface form of the stimulus (e.g., whether motion is implied or apparent), and this hypothesis was bolstered by Hubbard's (1995a) finding that representational momentum for auditory sequences was not influenced by whether the auditory sequences were presented as smooth pitch glides (apparent motion) or as series of discrete inducing pitches (implied motion). Thus, if memory for targets moving in depth exhibits representational momentum, then the use of discrete and separate inducing stimuli should reveal that representational momentum. The use of discrete and separate inducing stimuli also has another advantage over the use of a smoothly changing stimulus: the discrete and separate inducing stimuli are more similar to the static pictorial scenes used in studies of boundary extension than a smoothly or continuously changing stimulus, and so the possibility of observing boundary extension may also be increased.

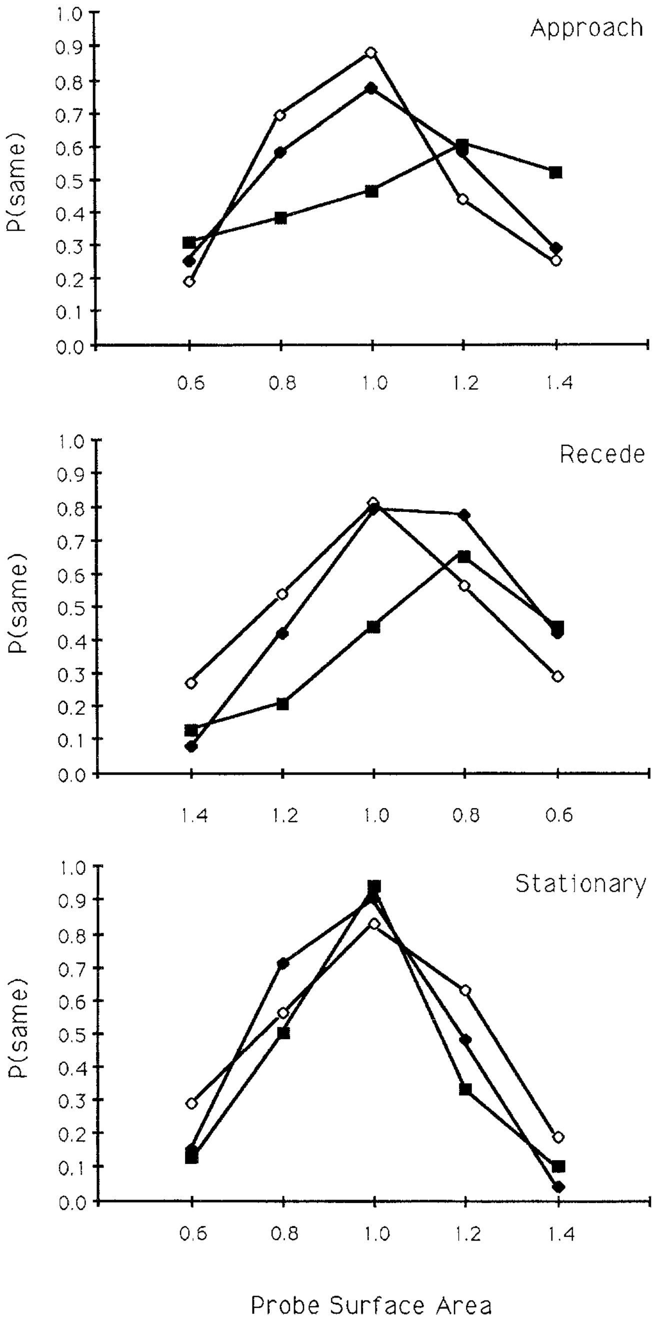

Fig. 2 The probability of a *same* response as a function of probe size in Experiment 1. Data from the approach condition are in the upper panel, data from the recede condition in the middle panel, and data from the stationary condition in the lower panel. (○ = slow; ● = medium; ■ = fast)

Table 1 Weighted mean estimates of displacement in Experiments 1, 2, and 3

	Target Velocity[a]		
	Slow	Medium	Fast
Experiment 1			
Approach	– 0.022	0.011	0.075
Recede	– 0.004	0.082	0.141
Stationary[b]	– 0.006	– 0.038	– 0.021
Experiment 2			
Approach	– 0.067	– 0.024	0.065
Recede	– 0.065	– 0.024	0.097
Experiment 3			
Approach	– 0.039	0.034	0.073
Recede	– 0.026	0.021	0.106
Rightward	0.067	0.093	0.146
Leftward	0.044	0.044	0.105

Note. For targets undergoing apparent motion, negatively signed displacements indicate shifts behind the final inducing stimulus (i.e., toward the observer for receding targets, away from the observer for approaching targets, to the left of the final inducing stimulus for rightward-moving targets, to the right of the final inducing stimulus for leftward moving targets), and positively signed displacements indicate shifts beyond the final inducing stimulus (i.e., away from the observer for receding targets, toward the observer for approaching targets, to the right of the final inducing stimulus for rightward moving targets, to the left of the final inducing stimulus for leftward-moving targets). For stationary targets, negatively signed displacements indicate shifts away from the observer and positively signed displacements indicate shifts toward the observer.

[a] Target Velocity was controlled by variation of the duration of each inducing stimulus and the ISI between presentations of successive inducing stimuli, so that the durations and ISIs were 500, 300, and 100 ms for the slow, medium, and fast conditions, respectively.

[b] Stationary targets did not exhibit a velocity per se, but were shown with the same stimulus durations and ISIs as and moving targets.

accurately, there would be 0% *same* responses for probes with surface areas of 0.6, 0.8, 1.2, and 1.4 and 100% *same* responses on probes with a surface area of 1.0.

Estimates of the sizes of the memory shifts were determined by calculation of the weighted mean (i.e., the sum of the products of the proportions of *same* responses and the surface area of the probe [as a proportion of the surface area of the final inducing stimulus] divided by the sum of the proportions of *same* responses) for each observer for each condition. The shift estimates were analyzed in a 3 (direction) × 3 (velocity) repeated measures ANOVA and are listed in Table 1. Direction was highly significant, $F(2,22) = 7.50$, $\mathrm{MSe} = 0.011$, $p < 0.01$; a post-hoc Newman-Keuls test ($p < .05$) revealed that the approach ($M = 0.02$) and recede ($M = 0.07$) conditions produced more positive shifts than the stationary ($M = -0.02$) condition. Velocity also influenced the magnitude of displacement, $F(2,22) = 5.67$, $MS_e = 0.009$, $p = .01$; a post-hoc Newman-Keuls test ($p < .05$) revealed that the fast velocity ($M = 0.065$) led to larger forward shifts than the slow velocity ($M = -0.008$), and the medium velocity ($M = 0.018$) produced shifts nonsignificantly different from the fast and slow velocities. Both the direction and the velocity effects were tempered by a Direction × Velocity interaction, $F(4,44) = 3.83$, $MS_e = .005$, $p < .01$, and as is shown in Table 1, the magnitude of forward displacement increased with decreases in stimulus duration and ISI (i.e., with increases in velocity) in both the approach and the recede conditions, whereas the magnitude of displacement did not change systematically with increases in stimulus duration and ISI in the stationary condition.

In the approach and recede conditions faster target velocities led to greater magnitudes of positive displacement (smaller magnitudes of negative displacement); this pattern is consistent with data on the displacement patterns of targets that undergo motion in the picture plane. Although the negative displacement for the slow-velocity targets may appear to be inconsistent with data on displacement for targets that move in the picture plane, in both Experiment 1 and in previous studies on motion in the picture plane, memory for faster targets is shifted beyond (i.e., in front of) memory for the slower targets and the ordering of displacement magnitudes as a function of target velocity is the same. Because the slower-velocity targets also had longer ISIs between inducing stimuli and a longer retention interval between the final inducing stimulus and the probe, the ISIs and retention intervals for slower-velocity targets were also longer than the ISIs and retention intervals for faster-velocity targets. It is possible that by having both ISIs and retention intervals increase with decreases in target velocity, that the effects of velocity were exaggerated, and a mechanism accounting for how this might explain the negative displacement for slower velocities is developed below.

The general decreases in the magnitude of forward displacement with increases in retention interval are consistent with Freyd and Johnson's (1987) findings on the time course of representational momentum in which the magnitude of representational momentum peaked with relatively shorter retention intervals and declined or reversed with relatively longer retention intervals. Freyd and Johnson (1987) suggested that this pattern could be accounted for by two different processes: a forward shift produced by representational momentum and a backward shift produced by memory averaging. Representational momentum dominated at shorter retention intervals and displaced memory in the direction of target motion, whereas memory averaging dominated at longer retention intervals and displaced memory toward the central tendency or average coordinates of the inducing stimuli (i.e., memory averaging represents a regression to the mean in which the memory for the final inducing stimulus reflects an average of the spatial positions of all of the prior inducing stimuli).

Freyd and Johnson's (1987) two-component model of the time course of representational momentum may be easily extended to explain the pattern of displacements for targets moving in depth. In Experiment 1 the fast-velocity stimuli used the smallest retention interval, and the slow-velocity stimuli the largest retention interval, and so the retention intervals were longer for slow-velocity targets. Thus, memory averaging had a weaker effect on the fast-velocity targets and a stronger effect on slow-velocity targets. Not only was the effect of memory averaging greater for slow-velocity targets, but the slower velocity would also have resulted in a smaller effect of representational momentum. For fast-velocity (and short-retention interval) targets the effects of representational momentum were dominant over the effects of memory averaging, whereas for slow-velocity (and long-retention interval) targets the effects of memory averaging were dominant over the effects of representational momentum. The apparent strength of memory averaging for slow-velocity targets may also have been boosted by the longer stimulus durations that accompanied the longer ISIs and longer retention intervals.

Representational momentum theory predicted that memory for the final inducing stimulus in the stationary condition should not be systematically shifted either toward or away from the observer. Although the displacement away from the observer in the stationary condition was inconsistent with representational momentum, it was consistent with boundary extension. A t test comparing the average displacement of each observer in the stationary condition against a mean of zero revealed that the shifts were significantly less than zero, $t(11) = 1.93, p < .04$, which suggested that boundary extension did occur. The magnitude of boundary extension was much smaller than that previously reported by Intraub and her colleagues, however, and the curves shown in Figure 1 are less skewed than is usually seen boundary-extension data. Nevertheless, a significant shift in memory for stationary targets away from the observer was found in the absence of the meaningful scene contexts used by Intraub and her colleagues, thus suggesting that at least a small magnitude of boundary extension could also occur with stimuli that were less scene-like or meaningful.

Experiment 2

Close inspection of the shift data in Table 1 suggests a trend that receding targets exhibit larger positive displacements than do approaching targets; indeed, in the post-hoc Newman–Keuls test the difference between approach and recede conditions almost attained significance. In Experiment 1 the final inducing stimulus subsumed the same visual angle in both the approach and the recede conditions; therefore, the first three inducing stimuli in the recede condition were larger than the first three inducing stimuli in the approach condition. It may be this difference in the average visual angle of the inducing stimuli between conditions, rather than any differences in the direction of motion per se, that produced the trend toward larger shifts for receding motion. In Experiment 2 the inducing stimuli for both approach and recede conditions were drawn from the same set of four stimuli, and so any differences due to the overall magnitude of the inducing stimuli should be eliminated.

Method

Participants. The observers were 12 undergraduates drawn from the same subject pool used in Experiment 1, and none of the observers had participated in that experiment.

Apparatus. The apparatus was the same as in Experiment 1.

Stimuli. The inducing stimuli were the same as those used in the recede condition in Experiment 1. For the recede condition the inducing stimuli were shown in order of decreasing visual angle, and for the approach condition the inducing stimuli were shown in order of increasing visual angle. Thus, while the final inducing stimulus differed in visual angle between approach and recede conditions, the inducing stimuli as a group did not differ in the overall average visual angle. Because the primary aim of the experiment was to use the same set of inducing stimuli in all trials, a stationary condition was not included. Probes for the recede condition were the same as those used in Experiment 1. Probes for the approach condition were black outline squares measuring 141, 161, 181, 198, or 214 pixels, and probe sizes for the approach condition were chosen in order to insure that the middle probe was the same as the final inducing stimulus and that the other probes differed by either 20% or 40% of the surface area of the final inducing stimulus. Target velocities (i.e., the duration of each inducing stimulus and the ISI between inducing stimuli) and retention intervals were the same as in Experiment 1. Each observer received 180 trials (2 directions × 3 velocities × 5 probes × 6 replications) in a different random order.

Procedure. The procedure was the same as in Experiment 1.

Results and discussion

The choice probabilities are displayed in Figure 3, and the x axes for the approach and recede conditions have been labeled so that the right side of each x axis lists probes beyond the final inducing stimulus (i.e., depths through which the inducing stimuli had not passed) and the left side of each x axis lists probes behind the final inducing stimulus (i.e., depths through which the inducing stimuli had passed).

Estimates of memory shifts were calculated as in Experiment 1, and the shift estimates were analyzed in a 2 (direction) × 3 (velocity) repeated measures ANOVA and are listed in Table 1. Direction did not influence the magnitude of shift, $F(1,11) = 0.81$, $p = .39$, nor was the Direction × Velocity interaction significant, $F(2,22) = 0.60$, $p = .56$. Velocity significantly influenced the magnitude of displacement, $F(2,22) = 29.63$, $MS_e = 0.005$, $p < .01$, and a post-hoc Newman–Keuls test ($p < .05$) revealed that all pairwise comparisons between the slow ($M = -0.07$), medium ($M = -0.02$), and fast ($M = 0.08$) velocities were significant.

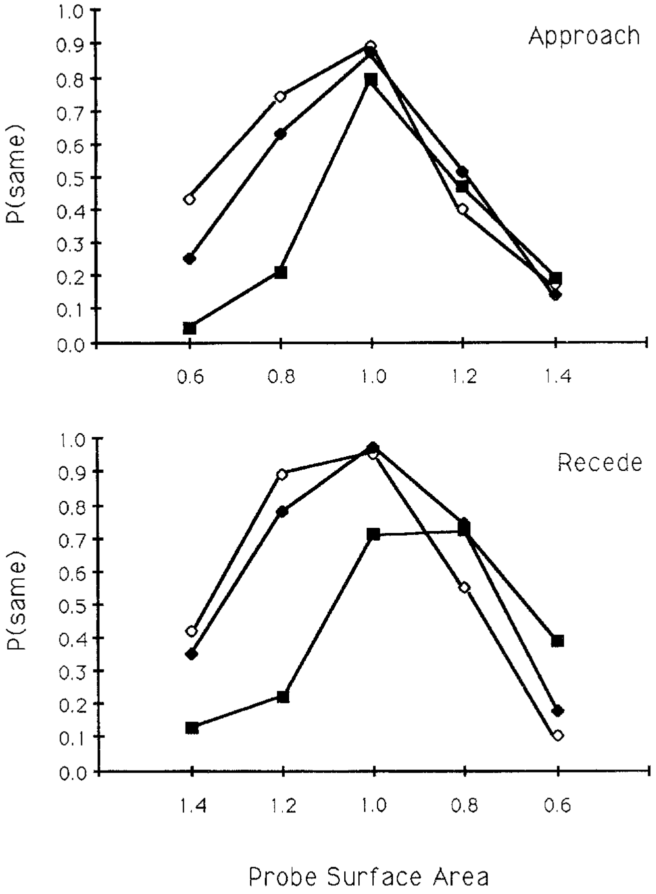

Fig. 3 The probability of a *same* response as a function of probe size in Experiment 2. Data from the approach condition are in the upper panel, and data from the recede condition in the lower panel. (○ = slow; ● = medium; ■ = fast)

No significant differences in the magnitude of displacement between approaching and receding motion were observed, and so the trend toward larger magnitudes of displacement for receding motion observed in Experiment 1 may have resulted from differences in the visual angles of the inducing stimuli in that experiment rather than from differences in the direction of motion per se. As in Experiment 1, faster targets produced larger magnitudes of positive displacement (smaller magnitudes of negative displacement); in fact, in Experiment 2 the slow- and medium-velocity targets produced negative displacement and only the fast-velocity target produced positive displacement.[3] The positive

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[3] The stimulus displays for the approach and recede conditions in Experiments 1 and 2 may be somewhat reminiscent of Kelly and Freyd (1987; Exp. 5) who presented observers with inducing square stimuli which appeared to shrink or grow in size and with probes that were either slightly smaller, slightly larger, or the same size as the final inducing stimulus. Kelly and Freyd's stimuli were similar to the approach and recede stimuli in Experiment 1 (i.e., the final inducing stimulus was the same size in both shrink and grow conditions), and they explicitly instructed their observers to compare the size of the probe with their memory for the size of the final inducing stimulus. Even though Kelly and Freyd framed their experiment as one involving changes in size, they noted that their displays were also consistent with a perspective transformation of an object approaching toward or receding from the observer. Although Kelly and Freyd did not vary velocity, the ISI of 250 milliseconds they used is between the fast and medium velocities in Experiments 1 and 2, and so the positive displacement Kelly and Freyd reported is consistent with the displacement patterns observed in Experiments 1 and 2.

displacement for fast-velocity targets and the negative displacement for slow-velocity targets in both Experiments 1 and 2 is consistent with the two-component model of the time course of representational momentum proposed by Freyd and Johnson (1987) for picture-plane motion with fast-velocity targets reflecting primarily the initial forward displacement and the slow-velocity targets reflecting primarily the subsequent memory averaging.

Experiment 3

The increasing positive displacements (decreasing negative displacements) with increases in target velocity found in Experiments 1 and 2 parallel the pattern found for picture-plane motion, but the negative displacements for targets moving at the slow velocity in Experiments 1and 2 suggest that the overall magnitude of displacement may be less for targets moving in depth than for targets moving in the picture plane. In other words, even though the form of the displacement functions (and the ordering of displacement magnitudes as a function of target velocity) may be similar for motion in depth and motion in the picture plane, the displacement functions for motion in depth may be shifted downward (toward smaller values) compared with the displacement functions for motion in the picture plane. In order to have more confidence in this hypothesis, it is desirable to present both picture plane and depth motion within the same experiment and to compare directly whether the direction (i.e., beyond or behind the final inducing stimulus) and magnitude of displacement for motion in depth matches the direction and magnitude of displacement for motion in the picture plane.

Method

Participants. The observers were 12 undergraduates drawn from the same subject pool used in Experiment 1, and none of the observers had participated in the previous experiments.

Apparatus. The apparatus was the same as in Experiment 1.

Stimuli. The depth stimuli were the same as in Experiment 2. The inducing stimuli for the picture-plane stimuli consisted of outline squares 81 pixels in length (the same size as one of the intermediate squares used in the inducing sequence for approach and recede motion), which portrayed horizontal motion in either a rightward or a leftward direction. Given that the length of each side of the square area in the approach and recede conditions changed by a factor of 1.5 between adjacent inducing stimuli moving in depth, the coordinates along the *x* axis for each of the inducing stimuli in the picture plane were chosen so that the ratio of side length to the distance traveled between each inducing stimulus was also 1.5. This yielded a shift of 54 pixels between each of the inducing stimuli. Given that the lengths of the sides of the probes in Experiments 1 and 2 were either approximately 10% or 20% larger or smaller than the lengths of the sides of the final inducing stimuli, the probes for picture-plane motion were placed either 10% or 20% of the length of each side away from the final inducing stimulus. The *y* coordinates of each side of the target were constant across the inducing and probe stimuli within each trial. The *x* coordinates of the probe appeared at one of five locations in relation to the *x* coordinates of the final inducing stimulus; -16, $-8, 0$, $+8$, or $+16$ pixels. Negatively signed probes indicate *x* coordinate values behind the actual vanishing-point coordinates and through which implied motion of the inducing stimuli would have previously passed (i.e., left of rightward stimuli and right of leftward stimuli), and positively signed probes indicate *x* coordinate values beyond the actual vanishing-point coordinates and through which implied motion of the square would not have yet passed (i.e., right of rightward stimuli and left of leftward stimuli). Target velocities and retention intervals were the same as in Experiments 1 and 2. Each observer received 180 trials (4 directions × 3 velocities × 5 probes × 2 replications) in a different random order.

Procedure. The observers were first given a practice session consisting of 12 trials, randomly drawn from the experimental trials. Observers were instructed to interpret the displays as depicting an object that remained the same objective size, but was either moving in depth or moving in the picture plane, and examples of how the visual angle of an object changes when that object moves in depth and does not (significantly) change when that object moves in the picture plane were given. Observers initiated each trial by pressing a designated key, and the first inducing stimulus immediately appeared. After the probe appeared, observers judged whether it was the same as the final inducing stimulus and pressed a key marked *S* (for same) or a key marked *D* (for different) to indicate their response. Observers then initiated the next trial.

Results and discussion

The choice probabilities are displayed in Figure 4, and the *x* axes for all conditions have been labeled so that the right side of each *x* axis lists probes beyond the final inducing stimulus (i.e., locations through which the inducing stimuli had not passed) and the left side of each *x* axis lists probes behind the final inducing stimulus (i.e., locations through which the inducing stimuli had passed).

Estimates of memory shifts for the approach and recede conditions were calculated as in Experiment 1, and estimates of memory shifts for the rightward and leftward conditions were determined by the analogous procedure of calculating the sum of the products of the proportions of *same* responses and distance of the probe (in pixels) from the final inducing stimulus and dividing by the sum of the proportions of *same* responses for each observer for each condition. The shift estimates were analyzed in a 4 (direction) × 3 (velocity) repeated measures ANOVA and are listed in Table 1. Direction significantly influenced displacement, $F(3,33) = 8.45$, $MS_e = 0.005$, $p < .01$, and a planned comparison revealed that displacements for motion in depth ($M = 0.03$) were significantly less than displacements for motion in the picture plane ($M = 0.08$), $F(1,11) = 14.14$, $MS_e = 0.008$, $p < .01$. As in Experiments 1 and 2, velocity influenced the magnitude of displacement, $F(2,22) = 12.33$, $MS_e = 0.009$, $p < .01$, and a post-hoc Newman–Keuls test ($p < .05$) revealed

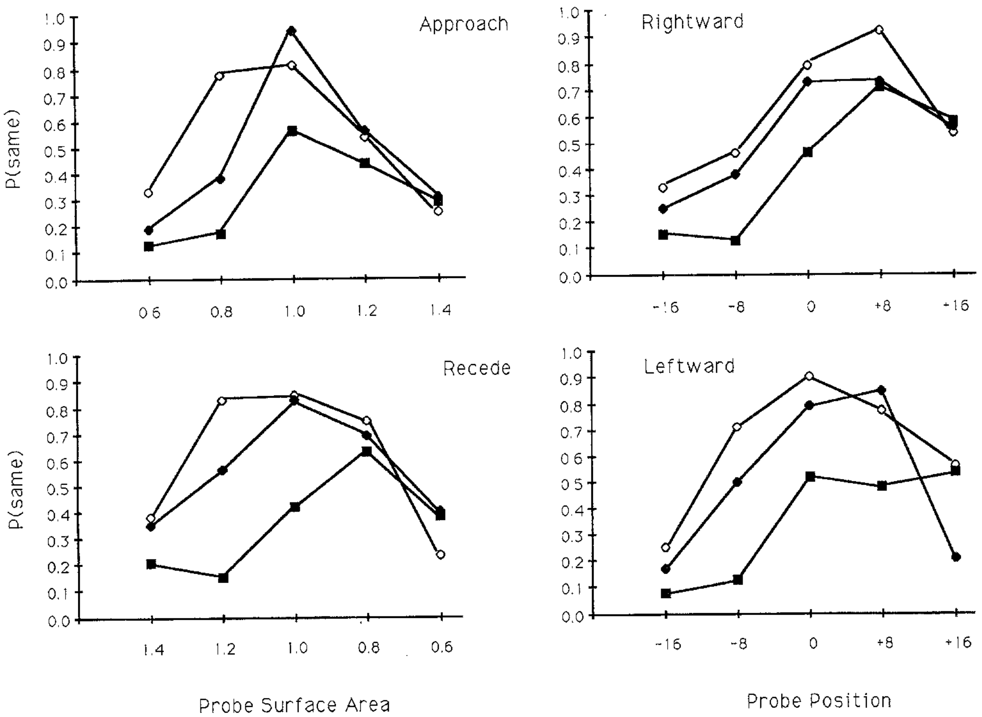

Fig. 4 The probability of a *same* response as a function of probe size in Experiment 3. Data from the approach and recede conditions are in the left column; data from the rightward and leftward conditions are in the right column (○ = slow; ● = medium; ■ = fast)

that fast velocities ($M = 0.11$) led to larger forward shifts than either medium ($M = 0.05$) or slow ($M = 0.01$) velocities did. The Direction × Velocity interaction did not approach significance, $F(2, 20) = 0.74$, $p = .62$.

Movement in depth led to smaller overall magnitudes of displacement than did movement in the picture plane. There are at least two different ways in which this decrease in the overall magnitude of displacement for targets moving in depth may have been produced. One way would be to multiply each displacement value by some fraction less than 1, and a second way would be to subtract a constant from each displacement value. The first method would not change the sign of any individual displacement value or the y intercept of the displacement function but would decrease the slope of the displacement function, whereas the second method could change the sign of an individual displacement value or the y intercept of the displacement function but would not change the slope of the displacement function. These different methods have different implications for theories of displacement. If the differences in displacement are due to changes in the slope, then some type of interaction between representational momentum, memory averaging, or some other factor is suggested; if the differences in displacement are due to changes in the sign of some displacement values or in the y intercept, then a main effect of representational momentum, memory averaging, or some other factor is suggested.

If the displacement magnitudes for each direction of target motion from Experiment 3 (given in Table 1) are plotted as a function of target velocity, then the slopes for each displacement function are seen to be positive. Furthermore, the displacement functions seem more consistent with the notion of a main effect of representational momentum, memory averaging, or some other factor because the slopes of the displacement functions for motion in depth and motion in the picture plane do not differ significantly. In fact, had such a difference existed, it would have been revealed as a significant Direction × Velocity interaction in the analysis, but this interaction did not approach significance. The interaction notion based on a shallower slope for motion in depth was not supported; in fact, the trend was in the opposite direction and for the slopes for motion in depth to be steeper than the slopes for motion in the picture plane. Furthermore, the y intercepts for motion in depth appeared to be smaller than the y intercepts for motion in the picture plane.

If the smaller overall magnitude of displacement for motion in depth is due to a main effect of representational momentum or memory averaging, then the decreased magnitude of displacement for motion in depth may result from either decreases in the initial representational momentum or increases in the subsequent memory averaging. A decrease in the initial representational momentum may be related to the decrease in the magnitude of the retinal space (two-dimensional picture-plane coordinates) crossed in a given unit of time; a movement in depth would cross fewer retinal coordinate points than an equivalent movement in the picture plane, and so a movement in depth would be displaced forward a smaller absolute amount than an equivalent movement in the picture plane. An increase in the subsequent memory averaging may also be related to the decrease in the magnitude of retinal space crossed in a given unit of time. A movement in depth would spread activation over a smaller number of retinal coordinate points than an equivalent objective movement in the picture plane. If a given extent of objective movement produces a certain overall level of activation, then the activation level at each retinal coordinate point corresponding to the location of an inducing stimulus would be relatively stronger, which could result in a stronger contribution of memory averaging to the remembered position than if the activation were spread out over a larger area (see Hubbard, 1995c, for a more detailed discussion of activation patterns in the determination of displacement).

Two caveats must be noted, however. The microcomputer screen was oriented in the picture plane, and so motion in the picture plane could be directly portrayed, but motion in depth could only be indirectly portrayed. It is possible that the indirect portrayal of motion may lead to smaller magnitudes of representational momentum than the direct portrayal of motion, although this argument is weakened by Hubbard's (1995a) finding that the surface form of the stimulus does not influence the magnitude of representational momentum and by Freyd's (1993) argument that it is the nature of the underlying stimulus dimension, and not the way that the stimulus is presented, that influences whether representational momentum is obtained. Additionally, the comparison of motion in the picture plane and motion in depth reported here supposes that a change in the length of each side of each inducing stimulus in the depth conditions by a factor of 1.5 of size is an equivalent change to a horizontal shift of each inducing stimulus in the picture-plane conditions by a factor of 1.5 of length and that probe spacing by increments of 20% of surface area in the depth conditions is equivalent to probe spacing by increments of 10% of length in the picture-plane conditions. To the extent that the changes in surface area are not equivalent to the changes in translation, then the claim that motion in depth produces smaller magnitudes of displacement than motion in the picture plane is questionable.

Experiment 4

Both representational momentum (Freyd & Johnson, 1987) and boundary extension (Intraub, 1992; Intraub et al., 1992) have been hypothesized to be dynamic processes that result from the operation of two separate components. The first component extrapolates memory in the direction most consistent with past experience. In representational momentum such an extrapolation includes the next likely position just beyond the target's actual position, and in boundary extension such an extrapolation includes the next likely elements just beyond the boundary of the scene. The second component shifts memory in the direction of a central tendency or regression to the mean. In representational momentum such a memory averaging shifts memory back toward an average of the inducing stimuli, and in boundary extension such a memory averaging shifts memory toward an average of the stimulus set of pictorial scenes.

In Experiment 1 observers' memory for stationary targets appeared to be distorted by boundary extension. If the negative displacements in the stationary condition were produced by boundary extension, then it should be possible to separate the effects of the initial unidirectional extrapolation and the subsequent memory averaging. Only one target size was used in Experiment 1, and so no effects of target set size on memory averaging could be examined. In Experiment 4 three different stationary target sizes were presented. If the displacement of stationary targets observed in Experiment 1 was due to boundary extension, and if boundary extension follows a time course similar to that of representational momentum, then memory for a stationary target tested after a relatively short retention interval should reveal displacement away from the observer and memory for a stationary target tested after a relatively long retention interval should reveal displacement toward the average of the three target sizes.

Method

Participants. The observers were 12 undergraduates from Eastern Oregon State College who received extra credit in an introductory psychology course in return for participating. All observers were naive to the hypotheses until after their data had been collected.

Apparatus. The apparatus was an Apple Macintosh IIcx microcomputer equipped with an Apple RGB color monitor. The microcomputer was approximately 60 cm away from the observers, but the observers could adjust this distance slightly in order to achieve maximum comfort and confidence in their responses.

Stimuli. The target was a solid black square on a white background. The square was one of three sizes on each trial: the small, medium, and large squares were 40, 80, and 120 pixels (100, 200, and 300 min) along each side, respectively. The length in pixels along each side of the probe was one of nine sizes relative to the target: −8, −6, −4, −2, 0, +2, +4, +6, or +8. As a consequence of the probe sizes used, differences between the probes were a smaller portion of overall probe length for larger targets than for smaller targets. Probes conserved the same overall shape as the target (i.e., the target and all the probes were square), and the center of the probe was located at the same screen coordinates as the center of the target. Presentation time of the target (i.e., duration) and the ISI between the target and the probe were either 250 ms or 750 ms on each trial, and if the time course of boundary extension is similar to the time course of representational momentum documented in Freyd and Johnson (1987), then displacement should be observed after 250 ms and memory averaging after 750 ms. Each observer received 432 trials (2 durations × 3 sizes × 9 probes × 8 replications) in a different random order.

Procedure. The observers were first given a practice session consisting of 12 trials, randomly drawn from the experimental trials. Observers initiated each trial by pressing a designated key, and the target immediately appeared. The target was displayed for either 250 or 750 ms, and then the screen was cleared for a duration equal to the target duration. The probe then appeared, and the observers judged whether it was the same as the target and pressed a key marked *S* (for same) or a key marked *D* (for different) to indicate their response. Observers then initiated the next trial.

Results and discussion

The choice probabilities are shown in Figure 5, and the x axes for all conditions have been labeled so that the right side of the x axis lists probes that were larger than the target and the left side of the x axis lists probes that were smaller than the target.

Estimates of memory shifts were determined by calculating the sum of the products of the proportions of *same* responses and distance of the probe (in pixels) from the target and dividing by the sum of the proportions of *same* responses for each observer for each condition. The shift estimates were analyzed in a 2 (duration) × 3 (size) repeated measures ANOVA and are listed in Table 2. Target size influenced memory shift, $F(2,22) = 18.08$, $MS_e = 0.85$, $p < .001$; a post-hoc Newman–Keuls test($p < .05$) revealed that all pairwise comparisons between the small ($M = 0.42$), medium ($M = -0.69$) and large ($M = -1.13$) targets were significant. Although the differences in probe size as a proportion of target size might have predicted the larger absolute shifts for larger targets, it would not have predicted the significant Size × Duration interaction, $F(2,22) = 28.57$, $MS_e = .37$, $p < .001$; as is shown in Table 2, after 250 ms, memory for each target size was shifted toward a smaller size (i.e., demonstrated boundary extension), whereas after 750 ms, memory for each target size was shifted toward an average of the three target sizes (i.e., demonstrated memory averaging). This interaction is precisely what we would have expected if memory for the stationary targets was influenced by a two-component boundary-extension process. A t test comparing the average displacement of each observer in the 250 ms ISI condition against a mean of zero revealed that the shifts were significantly less than zero, $t(11) = 2.59$, $p < .02$. The effect of duration was not signiciant, $F(1,11) = 0.85$, $p = .38$.

The data conform to a pattern consistent with Intraub et al.'s (1992) two-component model of boundary extension; specifically, at a relatively shorter duration memory was displaced away from the observer, and at a relatively longer duration memory was displaced toward an average or central tendency of the target sizes. Furthermore, the time course of the extrapolation and memory averaging components in the apparent boundary extension in Experiment 4 is similar to the time course of the extrapolation and memory averaging components in representational momentum in Freyd and Johnson (1987). The similarity of the data in Experiment 4 to that predicted by Intraub's two-component model suggests that simple featureless targets presented in the absence of a context or scene may undergo boundary extension, but this suggestion initially appears contrary to Intraub et al.'s (1992) claim that boundary extension arises in part from the activation of scene schemata because the highly artificial targets in Experiment 4 were presented on a featureless white background which presumably would not have evoked scene schemata.

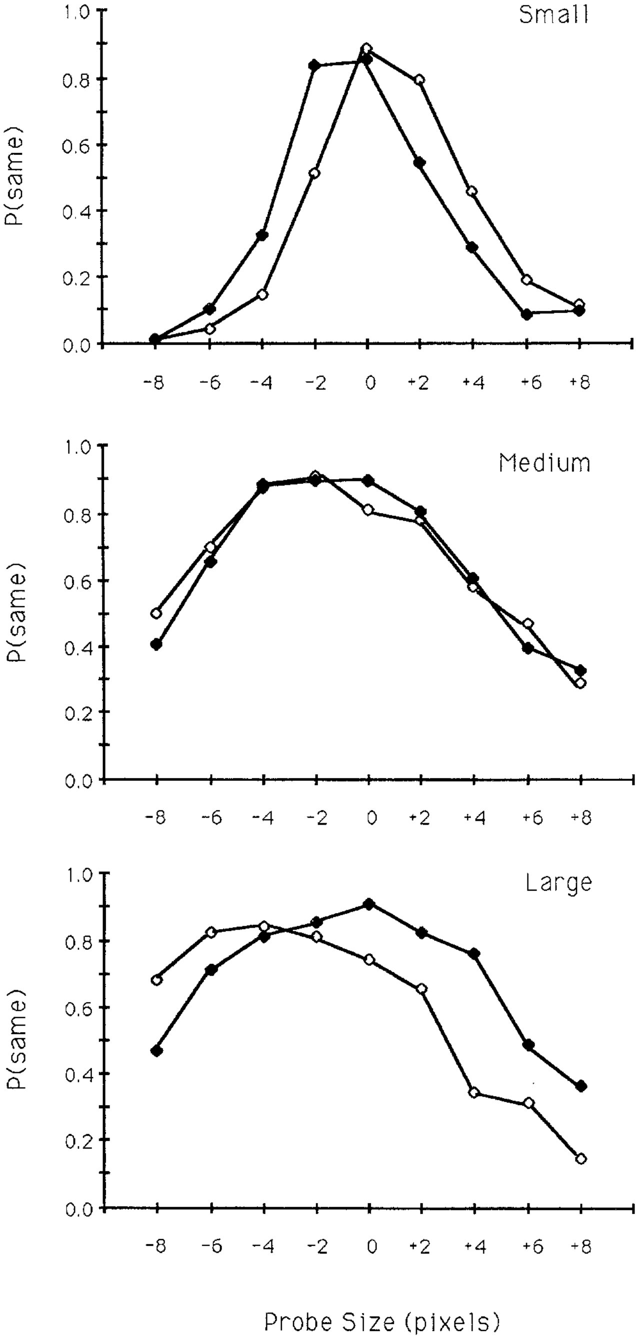

Fig. 5 The probability of a *same* response as a function of probe size in Experiment 4. Data from small targets are in the upper panel, data from medium targets in the middle panel, and data from larger targets in the lower panel (○ = long duration; ● = short duration)

Table 2 Weighted mean estimates of displacement in Experiment 4

	ISI	
	250 ms	750 ms
Target size		
Small	− 0.16	1.01
Medium	− 0.60	− 0.77
Large	− 0.38	− 1.87

Note. The sign of the displacement indicates the direction of shift from the final implied location such that negatively signed values indicate displacement away from the observer and positively signed shifts indicate displacement toward the observer

There are at least two possible explanations for why boundary extension may have been evoked in the apparent absence of scene context in Experiment 4. One possible explanation is that boundary extension, like representational momentum, may have become incorporated into the representational system. If a displacement mechanism has become incorporated into the representational system, then information regarding target identity or content may not be necessary in order for that type of displacement to manifest (see Hubbard, 1995c). In this case any information regarding the scene or context would be superfluous. A second possible explanation is that the observers' perception was not limited to just the computer screen and that observers perceived the stimuli on the screen as part of the larger scene of the experimental room. In this case the task did evoke a larger scene beyond the edges of the computer screen, and it was this greater context that resulted in the occurrence of boundary extension.

The data suggestive of boundary extension in Experiment 4 and the appeal to the experimental room as offering scene context appear at odds with Legault and Standing (1992), who found boundary extension in memory for photographs, but failed to find boundary extension in memory for line drawings. The target objects in their photographs and line drawings were the same, but the photographs contained background context and the line drawings did not contain background context. There were many methodological differences between Experiment 4 and Legault and Standing (1992) which may have contributed to the apparent differences in boundary extension, however. For example, the relative sizes of the stimuli may have differed. The target and background computer screen in Experiment 4 occupied a small visual angle. Although Legault and Standing do not report the size of their stimuli, they do report that the stimuli were in the form of slides projected on a wall. It may be that the stimuli in Experiment 4 occupied a sufficiently small percentage of the visual field to allow context in the form of the experimental room to be integrated into memory and that the stimuli in Legault and Standing's experiment occupied a larger percentage of the visual field and left less room for the context of the experimental room. Legault and Standing also used more complex targets than those used in Experiment 4. Clearly, determining the constraints that govern when boundary extension is or is not exhibited remains an area for further research.

Experiment 5

Experiment 4 suggested that boundary extension could be found for simple square stimuli in the absence of any elaborate surrounding scene or context. If boundary extension indeed does occur with such simple stimuli, then memory should be shifted toward a smaller visual angle. If memory is shifted toward a smaller visual angle, then observers should be more likely to remember the outer edge or perimeter of the target as being closer to the previous location of the center of the target than it actually was. In other words, when observers indicate the remembered location of one edge of the target, they should be more likely to indicate a location inside the previous perimeter of the target than a location outside the previous perimeter of the target. For example, observers should be more likely to remember the top edge as being slightly lower than the actual previous location of the top edge and more likely to remember the bottom edge as slightly higher than the actual previous location of the bottom edge. In Experiment 4 observers were presented with a stationary target, and after the target had vanished, the observers received an auditory cue instructing them to indicate the previous location of either the top or bottom edge of the target.

Method

Participants. The observers were 16 undergraduates drawn from the same subject pool used in Experiment 4, and none of them had participated in that experiment.

Apparatus: The apparatus was the same as in Experiment 4.

Stimuli. The target was a filled black square presented against a white background, and the target was drawn at one of six sizes on each trial: 20, 60, 100, 140, 180, or 220 pixels (0.83, 2.50, 4.17, 5.83, 7.50, 9.17°) along each side. The target was visible for one of three durations on each trial: 500, 1,000, or 1,500 ms. The auditory cue on each trial was either a 2,000 Hz tone or a 250 Hz tone and would play for 250 ms. Each observer received 360 trials (3 durations × 2 edges × 6 sizes × 10 replications) in a new random order.

Procedure. The observers were first given a practice session consisting of 12 trials, randomly drawn from the experimental trials. Observers initiated each trial by pressing a designated key, and the target immediately appeared. The target was displayed for either 500, 1000, or 1500 ms, and then the screen cleared. Immediately after the target had vanished, the auditory cue was presented and the cursor became visible in the form of a crosshair. A high-tone (2,000 Hz) auditory cue instructed observers to position the horizontal line of the crosshair where the top edge of the target had been; a low-tone (250 Hz) auditory cue instructed observers to position the horizontal line of the crosshair where the bottom edge of the target had been. Observers used a computer mouse to position the cursor, and after the cursor had been positioned, they pressed a button on the mouse to record the screen coordinates of the cursor. Observers then initiated the next trial.

Results and discussion

The differences between the true vanishing point and the judged vanishing point along the y axis were calculated (judged coordinates along the x axis were not collected), and these differences are referred to as *Y displacement*. Positively signed Y displacements reflect judged positions beyond the previous location of the edges of the target (i.e., above the top edge or below the bottom edge), and negatively signed Y displacements reflect judged positions within the areas previously occupied by the interior of the target (i.e., below the top edge or above the bottom edge).

The Y displacements were analyzed in a 3 (duration) $\times$ 2 (edge) $\times$ 6 (size) repeated measures ANOVA and are displayed in Figure 6. Size clearly had a significant effect on Y displacement, $F(5,75) = 37.92$, $MS_e = 132.32$, $p < .001$, as larger targets demonstrated larger magnitudes of negative Y displacement. The negative Y displacements indicate that memory was displaced inside the edges of the target; in other words, memory for the target was shifted toward a smaller visual angle. This is exactly the pattern we would expect to result from boundary extension. Interestingly, if the absolute magnitude of each Y displacement value was divided by the length of the side of the target that produced that Y displacement value, the resultant ratio (0.08) was nearly identical across all target sizes. Size also interacted with Duration, $F(10,150) = 3.36$, $MS_e = 23.63$, $p < 0.01$, and as is shown in Figure 6, this reflected a slight tendency for larger targets to exhibit greater magnitudes of negative Y displacement with shorter durations. Edge did not significantly influence Y displacement, $F(1,15) = 2.17$, $p = .16$, although there was a trend for judgements of the top edge ($M = -11.66$) to exhibit greater magnitudes of negative Y displacement than judgments of the bottom edge ($M = -7.52$). No other factors were significant.

When observers marked the remembered location of either the top or the bottom edge of a target, they indicated a location that was inside the actual previous perimeter of the target, and this pattern suggests that memory for the target was shifted toward a smaller visual angle. These data are fully consistent with the occurrence of boundary extension because a shift of the target edges inward is geometrically equivalent to a displacement of the target away from the observer. Larger targets exhibited greater absolute magnitudes of negative Y displacement, which is consistent with Intraub and Richardson's (1989) finding that close-up pictures (i.e., targets subsuming larger visual angles) undergo more boundary extension that do wide-angle pictures (i.e., targets subsuming smaller visual angles).

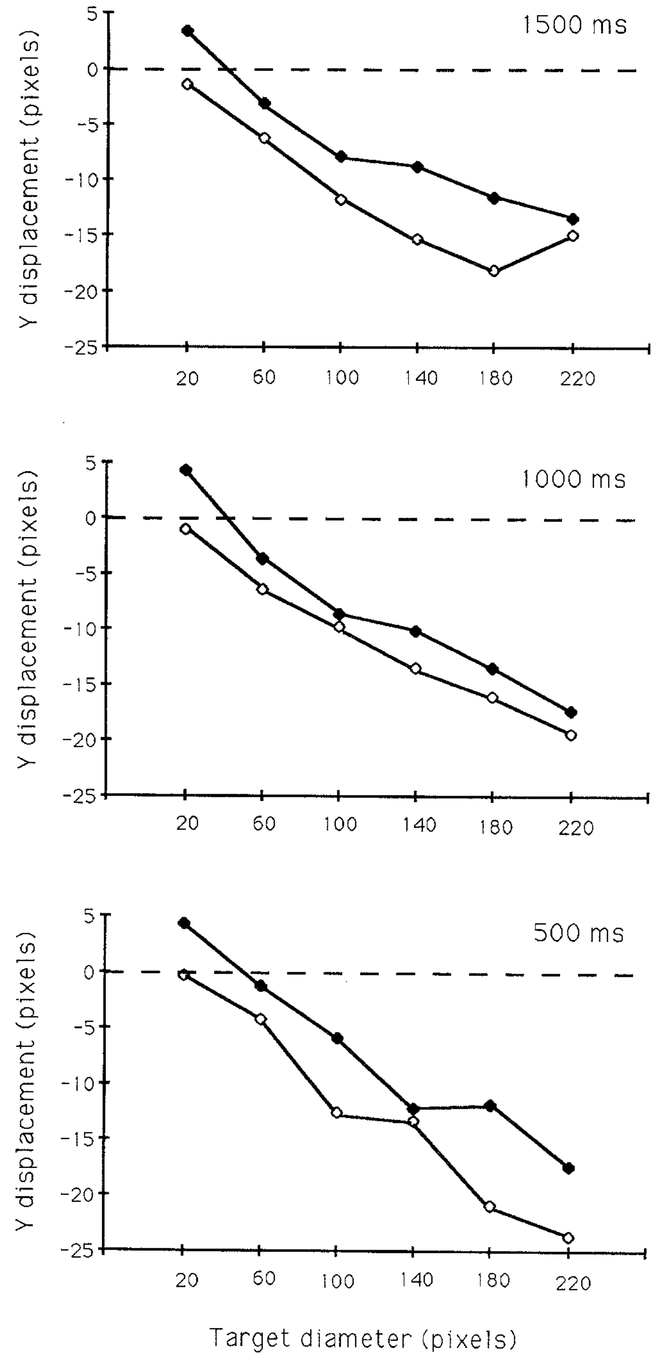

Fig. 6 Y displacement as a function of target size in Experiment 5. Data from the 1,500-ms condition are in the upper panel, those from the 1,000-ms condition in the middle panel, and data from the 500-ms condition in the lower panel (○ = top boundary; ● = bottom boundary)

Although memory for larger targets evidenced greater absolute magnitudes of negative displacement, the magnitude of negative displacement was nonetheless a constant proportion of the size of the target. This suggests that the magnitude of boundary extension may be determined by some sort of scaling process. This scaling of remembered intensity is also consistent with the finding that the psychophysical exponent for remembered area is generally smaller than the psychophysical exponent for perceived area (for review, see Algom, 1992; Hubbard, 1994), as both boundary extension and the smaller psychophysical exponent for remembered area suggest that the remembered area of a stimulus is less than the actual physical or perceived area. Alternatively, the increase in the absolute magnitude of negative *Y* displacement with larger targets may also reflect a ceiling effect for smaller targets because smaller targets are more limited in the absolute size of a potential negative *Y* displacement (as one side of a smaller target cannot displace inward as far because it would exit through the opposite side of the target).

General discussion

Targets moving in depth at faster velocities exhibited larger magnitudes of forward displacement (smaller magnitudes of backward displacement) than targets moving in depth at slower velocities. While targets moving in depth at faster velocities were displaced forward in the direction of target motion, those moving at the slowest velocity were actually displaced behind the target (i.e., toward the observer for receding motion and away from the observer for approaching motion). Given that targets moving at faster velocities also had shorter retention intervals, these patterns are consistent with the two-component model of the time course of representational momentum proposed by Freyd and Johnson (1987): an initial forward shift attributable to representational momentum that is dominant at shorter retention intervals and a backward shift attributable to memory averaging that is dominant at longer retention intervals. More specifically, memory for the target is initially displaced in the direction of target motion, and if the retention interval is sufficiently long, then this forward displacement is subsequently canceled out by a shift toward the mean position of the inducing stimuli produced by memory averaging.

In Experiment 3 the magnitude of forward displacement was greater for horizontal motion in the picture plane than for motion in depth. One possible explanation for the asymmetry in the magnitude of displacement between motion in depth and motion in the picture plane exploits the differences in the extents of the projections of motion in depth and motion in the picture plane upon the retina. As was illustrated in Figure 1 and discussed earlier, the more parallel the path of motion is to the picture plane, then the larger that displacement's visual angle and projection onto the two-dimensional retina; the more orthogonal the path of motion is to the picture plane, then the smaller that displacement's visual angle and projection onto the two-dimensional retina. If the magnitude of displacement is based in part on the extent of the retina traversed during target motion, then as the path of motion approaches the picture plane, a greater portion of the retina will be traversed in a given unit of time and the magnitude of displacement will be correspondingly greater.[4]

A second, albeit related, possible explanation for the asymmetry in the magnitude of displacement between motion in depth and motion in the picture plane is that the effects of memory averaging (which would shift memory backward toward the inducing stimuli previously presented) were relatively stronger for targets moving in depth than for targets moving in the picture plane because targets moving in depth overlap in their two-dimensional retinal coordinates much more than targets moving in the picture plane. The greater two-dimensional retinal separation between inducing stimuli presented in the picture plane would spread the activation over a larger two-dimensional area, and if the strength of activation falls off with increasing distance, then the activation strength of the averaged center of activation for the picture plane would be weaker than if the activation were spread out over a smaller two-dimensional area. If the remembered position of the target corresponds to this averaged center of activation (see Hubbard, 1995c), then the effects of memory averaging may therefore be weaker for targets that move in the picture plane than for targets that move in depth.

Memory for stationary targets in Experiments 1, 4, and 5 was also displaced away from the observer, a pattern that is consistent with boundary extension. Previous research on boundary extension has presented complex or naturalistic stimuli in a surrounding scene-like context, but the negative displacements observed in Experiments 1, 4, and 5 suggest that boundary extension may be found with simpler stimuli and simpler contexts. The initial displacement away from the observer, followed by the memory averaging observed in Experiment 4, is also consistent with Intraub et al.'s (1992) two-component model of boundary extension. It is also interesting that this rapid transition from dynamic extrapolation to memory averaging

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[4] Although this explanation is couched in terms of an image-retina system of motion detection in which a moving stimulus crosses a stationary retina, a similar logic also holds for an eye-head system in which the projection of a moving image is held in a constant retinal coordinate by tracking the moving object with a moving eye. In the former case information about extent arises from changes in retinal coordinates, whereas in the latter case information about extent arises from feedback from those muscles controlling eye movements. The extent to which image-retina and eye-head systems contribute to equivalent magnitudes of representational momentum awaits further empirical investigation, however.

parallels a similar transition and time course for representational momentum. In Experiment 5 the magnitude of negative displacement was shown to be a constant proportion of target size, which is in agreement with Intraub and Richardson's (1989; also Intraub et al., 1992) finding that close-up pictures may undergo more boundary extension than wide-angle pictures; specifically, in both Experiment 5 and in Intraub and Richardson (1989), target stimuli that occupied a larger visual angle (i.e., larger stimuli or close-up pictures) exhibited greater absolute magnitudes of boundary extension.

Displacements in depth consistent with either boundary extension or representational momentum were observed in all of these experiments. Given the similarities in the time course, as well as the similarities in extrapolation beyond the stimuli, the reliance on internalized expectations, and appeals to dynamic aspects of memory, it is possible that boundary extension and representational momentum may arise from either similar mechanisms or different facets of the same general displacement mechanism. These two types of displacement may differ more in their realms of application than in their fundamental mechanisms; representational momentum is observed when targets evoke motion schemata, and boundary extension is observed when targets evoke scene schemata. In other words, representational momentum and boundary extension may be special cases of a more general and deeper underlying extrapolation process that biases spatial memory by distorting memory in directions most consistent with past experience.

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