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A matter of design: No representational momentum without predictability

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When observers are asked to localize the final position of a moving target, a forward shift of the judged final position is observed. So far, the forward shift has been attributed to the influence of mental continuation of the final target position (representational momentum). However, studies investigating forward displacement have used highly predictable target motion. The direction of target motion and the final target position were often varied between subjects. Thus, observers may have expected the target to travel in a particular direction or vanish at a particular location before a given trial started. In this study, direction of motion and final position were treated as fixed or random factors. The forward shift and the reversal of the shift with time (memory averaging) were absent when both factors were randomized. Thus, the forward shift with implied motion is restricted to repeatedly observed motion sequences that allow for pre-trial motion prediction.

A topic that has received much interest in cognitive psychology is the question of how the mental system deals with dynamical events (e.g., Freyd & Finke, 1984; Freyd, Pantzer, & Cheng, 1988). It has been suggested that mental representations are inherently dynamic (Freyd, 1987). Consistent with this hypothesis, memories of the final position of a moving object are not accurate in the physical sense, but are distorted in a manner suggesting that the mental apparatus continues the motion of the object internally: When observers are asked to judge the final position of a moving object, the remembered position is shifted in the direction of motion (see Hubbard, 1995, for an overview). The localization error is referred to as forward displacement or forward shift. It has been assumed that analogous to the physical momentum of real-world objects, mental representations of moving objects take some time before coming to a halt.

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The inability to stop the mental representation of continuing motion is referred to as *representational momentum* (Freyd & Finke, 1984). In this paper, the term representational momentum is used to refer to an explanation of the forward displacement in terms of mental continuation, not as a term for the empirical observation.

Two types of motion have been used to study representational momentum, implied rotation used primarily by Freyd and colleagues (e.g., Freyd & Finke, 1984; see Figure 1) and smooth linear motion used primarily by Hubbard and colleagues (e.g., Hubbard & Bharucha, 1988). As there is reason to believe that the two types of motion differ with respect to the type of eye movements they elicit, the present contribution primarily discusses results obtained with implied motion. As outlined in the Discussion, smooth stimulus motion elicits smooth pursuit eye movements and the forward localization error is absent if smooth pursuit is suppressed (Kerzel, 2000a; Kerzel, Jordan, & Müsseler, in press; although see Müsseler, Stork, & Kerzel, this issue, for an exception). Implied motion may not elicit pursuit eye movement because of its discontinuous nature (Becker & Fuchs, 1985; Yasui & Young, 1975). Rather, the discrete onsets of the stimulus at different locations with implied motion are effective stimuli for saccades (e.g., Deubel & Schneider, 1996).

A central piece of evidence for the continuous nature of dynamic representations was the time course of the memory shift. Freyd and Johnson (1987) presented observers with a series of images of a rectangle at different orientations (see Figure 1). The rectangle was presented three times at different degrees of rotation such that rotation of the rectangle about its centre was implied. Observers were instructed to memorize the orientation of the third presentation. After retention intervals (RIs) varying between 10 and 900 ms, a fourth rectangle, the probe stimulus, was presented. Observers were asked to compare the orientation of the probe stimulus with that of the third inducing stimulus and to judge whether they were at the same or at a different orientation. Freyd and Johnson showed that observers were more likely to accept probe stimuli rotated further in the direction of motion as being in the same position than probe stimuli rotated opposite the direction of motion. Thus, the judged final position deviated from the actual final position in the direction of rotation. Consistent with the assumption of dynamic mental representations, this effect increased for 200–300 ms after stimulus offset. After 200–300 ms, however, the forward shift decreased, and in some conditions, a shift of the remembered position opposite to the direction of implied motion was observed. The reversal of the forward shift was attributed to subsequent memory averaging of the target's previous positions.

It is important to note that in the studies of Freyd and colleagues, direction of implied motion was almost exclusively treated as a between-subjects variable (Finke & Freyd, 1985; Finke, Freyd, & Shyi, 1986; Freyd & Finke, 1984, 1985; Freyd & Johnson, 1987; Kelly & Freyd, 1987). That is, a given participant was

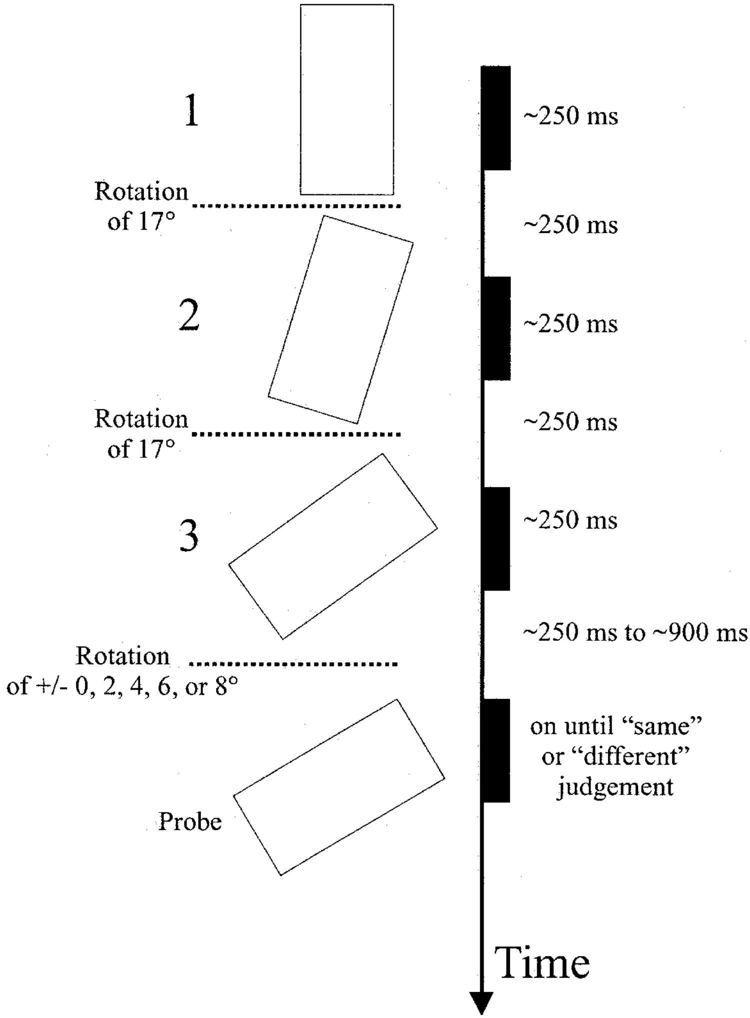

Figure 1. Display sequence. The rectangle was presented four times at different orientations. Unlike in the graph, its centre was always at the same position on the screen. The first three presentations (1–3) are referred to as inducing stimuli, the fourth presentation as probe stimulus. In the experiments of Freyd and colleagues (e.g., Freyd & Finke, 1984), each presentation lasted for about 250 ms, and successive presentations were separated by blank intervals of about 250 ms. In the present experiment, these times were changed to 302 and 156 ms. The orientation of the rectangle was changed by 17° between presentations. The interval between the last presentation of the inducing stimuli and the probe stimulus is referred to as retention interval. It was varied parametrically between 10 and 1700 ms in Freyd and Johnson (1987). Only retention intervals of and 260 and 936 ms were realized in the present experiment. The orientation of the probe stimulus differed by +8 to –8° from that of the inducing sequence. Positive and negative numbers indicate that the probe stimulus was rotated further in and opposite the direction of rotation, respectively. Subjects were asked to judge whether the last inducing stimulus had the same orientation as the probe stimulus.

presented with either clockwise, or counterclockwise rotation throughout the experimental session. Further, the final position of the rectangle was the same for all observers. From the viewpoint of standard experimental methodology, this choice of design is rather peculiar. Typically, the goal of an experiment is to test whether characteristics of single events influence a dependent measure. To ensure that the content of a specific trial reflects only the events of that trial, it is often appropriate to randomize the experimental variables within subjects; if events of previous trials do influence a given trial, then at least a randomization of the experimental variable will prevent a systematic bias from occurring. In the studies of Freyd and colleagues, however, no such randomization was performed. Quite to the contrary, a given participant saw the same sequence of inducing stimuli throughout the experiment. Thus, it is unclear whether the content of a given trial, or the repeated presentation of one and the same event accounts for the effect. When the direction of rotation and the final orientation of the rectangle remain constant throughout an experimental sitting, observers acquire knowledge about which positions the object will occupy at a certain time such that they may anticipate the final orientation of the rectangle at the very beginning of a trial *before* stimulus onset. Therefore, it is unclear whether the reason for the forward bias is the mental continuation of the implied motion occurring in each trial, or some multi-trial expectancy about the target's trajectory.

EFFECTS OF EXPECTATION

An explanation of the forward shift in terms of expectations was addressed by Finke (Finke & Freyd, 1985; Finke & Shyi, 1988). In Finke and Shyi's Experiment 2, the direction of motion was treated as a within-subjects variable to test whether participants formed a perceptual set for extrapolating the implied motion after observing the same direction of implied motion repeatedly. Using dot patterns that implied linear motion, Finke and Shyi found that compared to a design in which direction of motion was treated as a between-subject variable, the forward shift with within-subject variation was decreased, but still significant. Moreover, results of some later studies that did not directly address the expectancy issue suggested that the choice of design has an effect on the forward shift. Hubbard (1993) obtained no significant forward displacement with implied rotation and within-subject variation of the direction of motion. However, it may be that additional cues resulting from displaying oblique lines on a raster display may account for this null effect. Further, forward displacement was observed with linear implied motion, fixed final position and random direction of motion (Halpern & Kelly, 1993; Reed & Vinson, 1996). However, effects of target velocity and the characteristic time course (Freyd & Finke, 1985; Freyd & Johnson, 1987) were not obtained (Halpern & Kelly, 1993).

The finding that forward displacement is affected by the choice of design suggests that processes extending beyond a single trial contribute to the forward shift. These results are to some degree consistent with effects of event course anticipation on representational momentum. Verfaillie and d'Ydewalle (1991) investigated memory displacement for a rectangle undergoing implied periodical motion (see also Hubbard & Bharucha, 1988). They found that when memory for the position of the rectangle was probed at predictable reversal points of the rectangle's trajectory, the forward displacement was eliminated. That is, when the anticipated direction of motion was not forward, but backward, no memory displacement occurred. This suggests that expectations about the future path of a target influence judgements of the final position of the target. Of course, expectations about the trajectory of the target had to be acquired across trials, which corroborates the hypothesis that processes extending beyond a single trial influence the memory shift (for trial-by-trial variation of expectancy see Hubbard, 1994).

GOAL OF STUDY

The goal of the present study was to further investigate effects of multi-trial processes on forward displacement and memory averaging. In particular, predictability of the target's trajectory before stimulus onset was manipulated by using different designs. Previous studies investigating effects of implied motion on the forward shift used designs that involved a high degree of certainty about the direction of motion (rotation), and about the final position of the target. In the studies of Freyd and colleagues, direction of rotation (DR) was treated as a between-subjects variable and the final position (FP) of the inducing sequence was fixed for all observers. This treatment of the variables DR and FP implies that a given observer saw the same sequence of rectangles throughout the experiment. Therefore, the predictability of the target's trajectory before target onset was extremely high. In Finke and Shyi (1988), DR was varied within-subjects, but FP was kept constant. Thus, the number of possible starting positions was doubled, but the final position was still fixed. In Hubbard (1993) the starting position was fixed, but the number of possible final positions were doubled. This implied a lower degree of certainty about the trajectory of the target, but parts of the trajectory were still known before the target came on (see also Nagai, Kazai, & Yagi, this issue; Vinson & Reed, this issue).

In the present study, DR was either treated as a between-subjects variable, or as a within-subjects variable, and the FP of the rectangle was either fixed or varied randomly. Within-subject randomization of either one of the two variables decreases the level of predictability, that is, the level to which observers may anticipate future positions of the rectangle on the basis of previous trials. Importantly, I use *predictability* to refer to anticipation of the target's trajectory *before* target onset. As the same velocity of implied motion and the same number of target presentations was used throughout, anticipation of parts of the trajectory was possible once the first (or second) stimulus was shown. The possibility to anticipate target positions within a trial was roughly the same for all conditions.

With DR treated as a between-subject variable and random FP, the observer does not have certainty about where the target will disappear, but knows in which direction it will travel. With within-subject variation of DR and fixed FP, the observer does not have certainty about the direction in which the target will travel, but knows where it will disappear. When both DR and FP are randomized, the observer does not know in which direction the rectangle will be rotated, and does not know where it will disappear. Thus, the combination of within-subject DR and random FP is the only condition in which observers cannot anticipate the target's trajectory prior to the appearance of the target and use information from previous trials. That is, this is the only condition in which across-trial processes may be ruled out.

Effects of predictability may necessitate a change of our basic understanding of the forward shift and memory averaging. The standard explanation of the effect has been that internalization created mental analogues for various physical regularities such as momentum, gravity, friction, etc. (see Hubbard, 1995, for an overview). It was assumed that the mental analogue for momentum produced the forward distortion. Additionally, the mental extrapolation process was assumed to be modified by expectations about the trajectory of the target (Hubbard & Bharucha, 1988; Verfaillie & d'Ydewalle, 1991). Freyd and Finke (1989) metaphorically described the situation as a train going down a track in a switchyard. Setting a switch determines the track that the train might follow, but the train would still have to go some way. Thus, the direction in which the train's physical momentum is expressed depends on the setting of the switch. In the metaphor, expectations about the trajectory act as a switch on representational momentum, and we might expect repeated presentations to act as a similar switch, thus channelling displacement in a single specific direction.

The goal of the present study was to investigate whether the latter assumption of mental motion continuation resulting from the perception of implied motion holds true. In particular, it may be the case that the forward shift depends entirely on the predictability of the trajectory before trial onset. In other words, the study examined whether representational momentum, which presumably operates primarily after stimulus offset in trial *n*, is dependent on predictability, which derives from processes operating in trials n–x, that is, before stimulus onset in trial *n*. So far, it was assumed that representational momentum is channelled or modified by expectations (Freyd & Finke, 1989). The question here is whether there is representational momentum independent of predictability.

Method

A subset of the conditions in the study of Freyd and Johnson (1987) were replicated. Freyd and Johnson found that memory displacement was maximal with a RI of 250 ms due to representational momentum, and dropped off dramatically with a RI of about 900 ms due to memory averaging. Therefore, these RIs were chosen as they may reveal how the two apparently independent processes, representational momentum and memory averaging, depend on predictability. Further, implied rotation of a rectangle was used. To avoid aliasing, a dot outline figure was employed. DR was either varied within or between subjects and FP remained either fixed or was randomized.

Participants

A total of 52 students at the Ludwig-Maximilians University of Munich were paid for their participation. All reported normal or corrected-to-normal vision and were naïve as to the purpose of the study.

Apparatus and stimuli

The stimuli were created using a Matrox Millenium graphics card on a 21-inch (diagonal) screen with a refresh rate of 96 Hz. The display had a resolution of 1280 (H) × 1024 (V) pixels. In each trial, a sequence of four rectangles was presented. The first three rectangles are referred to as inducing stimuli, the fourth rectangle as probe stimulus. The rectangle measured 7° × 3.5° viewed from 50 cm and consisted of 12 white dots that were presented on a black background. As in Verfaillie and d'Ydewalle (1991), a rectangle outlined by dots was used to prevent observers from using cues arising from the inevitable aliasing of oblique lines on a raster display. The upright position of the rectangle was considered an orientation of zero degree. Orientations are reported with respect to the upright position and clockwise rotation. The inducing rectangles were shown for 302 ms, and successive presentations were separated by a 156 ms blank interval. Between successive presentations of the rectangle, its orientation was changed by 17°. Either 260 or 936 ms after offset of the final inducing stimulus, a probe rectangle was displayed with an orientation ±8, ±6, ±4, ±2, and 0° relative to the final orientation of the inducing rectangle. Positive or negative numbers indicate that the probe rectangle was rotated in or opposite the direction of rotation, respectively. The deviation of the probe orientation with respect to the orientation of the final element of the inducing sequence is referred to as *probe position*. The interval between the last stimulus of the inducing sequence and the probe stimulus is referred to as RI. In Freyd's work (e.g., Freyd & Johnson, 1987), stimulus presentation and blank intervals were typically 250 ms, lines were used instead of dots, and the RIs closest to the ones used here were 250 ms and 900 ms. The probe stimulus stayed on until observers gave their judgement. In the centre of the rectangle, a green fixation dot was continuously displayed. In Freyd's work, a fixation point was presented before the target stimulus appeared, but not during the sequence of implied motion.

Conditions

The different designs to manipulate the direction of rotation and the final position were realized between subjects in four different conditions. DR could either vary between subjects, that is, DR remained the same for a given participant (between subjects, BS), or it could vary from trial to trial (within subjects, WS). With between subject variation of DR (BS-DR), the rectangle was rotated in clockwise direction from an initial orientation of 0° for half of the observers. For the other half, it was rotated in counterclockwise direction from an initial orientation of 68°. Thus, the final orientation of the inducing sequence was 34° for all observers. With within-subject variation of DR (WS-DR), the direction of rotation varied unpredictably from trial to trial. FP was either fixed for all participants (F-FP) at 34° or it could vary randomly from trial to trial (R-FP). Sixteen observers were assigned to the condition WS-DR + F-FP, which replicates Freyd's design, ten observers to condition BS-DR + R-FP, and twelve observers to condition WS-DR + F-FP, and 14 observers to condition WS-DR + R-FP.

The conditions resulting from the factorial combination of probe positions (±8, ±6, ± 4, ±2, and 0°), and RIs (260 and 936 ms) were replicated 20 times per observer such that each observer worked through 360 experimental trials. For observers in WS-DR conditions, half of the trials were counterclockwise (CCW) and the other half clockwise (CW) rotations. Half of the observers in BS-DR conditions saw CCW rotations, the other half CW rotations.

Procedure

Observers were instructed to fixate the green dot at the screen centre. However, eye movements were not monitored. Head movements were restricted by a chin-forehead rest. They received about 15 practice trials drawn randomly from the experimental trials. To indicate whether the third and the fourth rectangle were at the same orientation or not, participants pressed one of two keys.

RESULTS

The proportions of "same" judgements are shown for each condition as a function of probe positions and RI in Figure 2. The weighted sum of "same" judgements was calculated as a measure of displacement (see Table 1). This score was calculated from the percentage of times that a participant responded "same" for each probe orientation, weighted by the deviation of the orientation

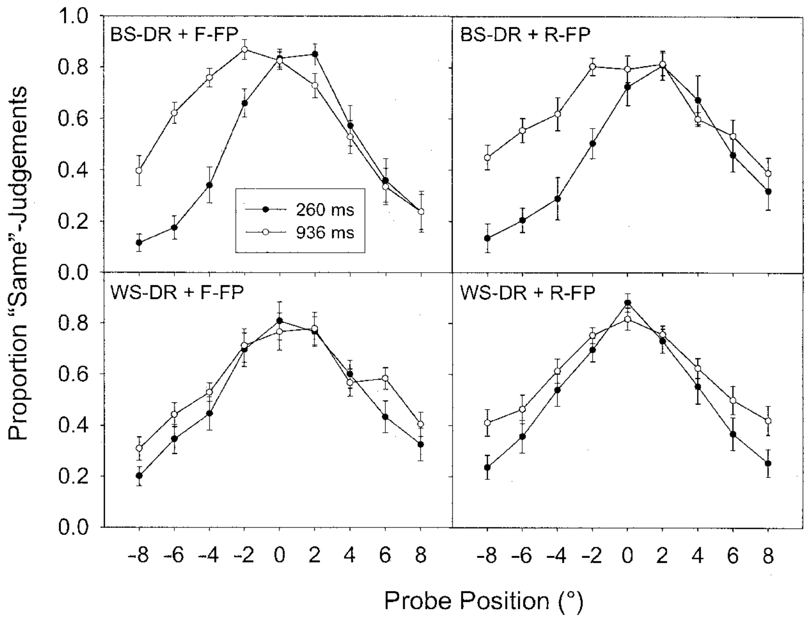

Figure 2. Proportion "same" judgements as a function of probe position, retention interval, and experimental design. Positive and negative probe positions indicate that the probe was rotated further in and opposite the direction of implied motion, respectively. BS-DR and WS-DR refer to between-subjects (BS) and within-subjects (WS) variation of the direction of motion (DR), respectively. F-FP and R-FP refer to fixed (F) and random (R) final position (FP) of the rectangle. Four conditions result from the combination of DR (BS, WS) and FP (F, R).

TABLE 1
Summary of results. Mean displacement in degrees or rotation and between-subject standard error (in brackets) is shown as a function of randomization of final position (fixed, random), design used to vary direction of rotation (between subjects, within subjects), and retention interval (260 ms, 936 ms)

		Final position			
		Fixed (F-FP)		*Random (R-FP)*	
	Retention interval	*260 ms*	*936 ms*	*260 ms*	*936 ms*
Direction of rotation	Between-subjects	3.4*	–4.2**	5.2**	–0.66, n.s.
	(BS-DR)	(1.3)	(1.35)	(1.35)	(0.9)
	Within-subjects	2.28*	1.9*	0.34, n.s.	0.35, n.s.
	(WS-DR)	(0.76)	(0.7)	(0.51)	(0.58)

Positive and negative numbers refer to displacement in and opposite the direction of rotation, respectively. *T*-tests compared mean displacement values to zero. Means significantly different from zero at the .025 level are marked by *, those significant beyond the .01 level by **. Means not significantly different are marked by n.s. (all *p*s > .5).

of the probe stimulus from the final orientation in the inducing sequence (–8° to +8°). Negative and positive displacement scores indicate mislocalization opposite and in the direction of motion, respectively. Differences between CCW and CW rotation were not evaluated because of the different types of comparisons that would be required (WS and BS), and the small number cell sizes for each condition (160 trials per participant in WS-DR conditions; only five observers in BS-DR + R-FP). Freyd (e.g., Freyd & Johnson, 1987) never reported effects of direction of rotation, such that collapsing across this factor may be legitimate.

A three-way ANOVA with DR and FP as between-subject, and RI as within-subject factors was conducted. The forward shift decreased from 2.7° with the short RI to –0.9° with the long RI, $F(1, 48) = 69.1$, $p < .0001$. There was a significant interaction of DR and FP, $F(1, 48) = 5.25$, $p < .05$, indicating that for fixed FP the forward shift was larger with random than with fixed DR (2.1° vs. –0.4°). In contrast, with random FP, the forward shift was larger with fixed than with random DR (2.3° vs. 0.3°). The interaction of DR and RI reached significance, $F(1, 48) = 61.89$, $p < .0001$. With fixed DR, the forward shift decreased with RI from 4.1° to –2.8°, whereas there was no difference between short and long RI with random DR (1.2° vs. 1.1°). Single *t*-tests evaluated whether the forward displacement was significantly different from zero (see Table 1). Further, it was evaluated whether the small and the long RI differed. They did so in condition BS-DR + F-FP, $t(15) = 7.59$, $p < .0001$, and in BS-DR + R-FP, $t(9) = 6.41$, $p < .0001$, not in the other conditions (*p*s > .6).

DISCUSSION

In the condition most closely resembling the study of Freyd and Johnson (1987), a replication of their pattern of results was obtained. When direction of rotation was treated as a between-subjects variable and the final position was fixed for all observers (BS-DR + F-FP), displacement in the direction of rotation was observed with the short RI, and a reversal of the displacement was observed with long RIs. Freyd and Johnson reported a similar reversal of the displacement, but found the displacement to be slightly positive with long RIs and an implied velocity comparable to the one used here. The different stimuli used, and the somewhat different presentation times may account for this discrepancy.

Modification of the standard condition BS-DR + F-FP by randomizing the final orientation of the inducing stimulus had very little effect on the pattern of displacement. In the BS-DR + R-FP condition, there was a forward shift with the short RI, and a reversal with the long interval. Unlike in the BS-DR + F-FP condition, displacement with the long RI was not significantly negative.

In contrast, treating the direction of rotation as a within-subject variable changed the pattern of displacement dramatically. When the direction of rotation varied from trial to trial, the difference between short and long RIs disappeared, both with fixed and random final position (WS-DR + F-FP and WS-DR + R-FP). That is, when observers did not have foreknowledge about the direction of motion in the next trial, memory averaging disappeared. When the final position of the rectangle was fixed in condition WS-DR + F-FP, displacement was positive regardless of RI. When the final position of the rectangle was random in condition WS-DR + R-FP, however, displacement was absent with both RIs. These results deviate markedly from those reported by Freyd and Johnson (1987). First, the typical time course of memory displacement was not observed. Freyd and Johnson found a decrease of RM with RIs longer than 200–300 ms that was taken as evidence for memory averaging. In the present study, no evidence for such a reversal could be obtained when there was within-subject variation of the direction of rotation. Thus, memory averaging depends on fixed expectations about the direction of motion. Second, with highly unpredictable implied motion, that is, when both final position and direction of motion varied randomly from trial to trial, no evidence of a forward shift could be obtained. Thus, the forward shift depends on knowledge about parameters of the target's trajectory. This finding is consistent with research by Finke and Shyi (1988), who found a reduction with decreased predictability. Note that this conclusion is limited to implied motion: With smooth linear motion and ocular pursuit of the target, forward displacement was obtained even with highly unpredictable final position of the target (Hubbard & Bharucha, 1988).

In summary, the results provide strong evidence for the view that processes extending beyond a single trial contribute to the forward displacement. The predictability of the target motion changed the time course of the displacement and its size. Therefore, displacement was not produced by the content of an individual trial, but by a sequence of trials. Most importantly, the displacement was absent in conditions in which predictability was minimal. Implications for theories relating forward displacement to internalized physical laws, and an alternative view in terms of perceptual processes are discussed.

Implications for theories of representational momentum

The assumption that the forward shift was (at least partially) due to representational momentum needs to be modified—if not abandoned—in light of the present data. The present study shows that the forward shift only occurs if observers have strong expectancies about where the target will vanish, or in which direction it will rotate. Thus, the sequence of implied motion itself is ineffective in eliciting a distortion of memory. Only if the implied motion stimulus was combined with expectancies about parameters of the motion trajectory did the forward shift occur. If the notion of representational momentum is to be maintained for stimuli undergoing implied motion, its scope has to be restricted to the rather limited class of repeatedly observed motion sequences. Notably, the stimulus in the present study only showed rotary motion such that even if direction of rotation and final position were unpredictable, the type of motion was strongly restricted and allowed for anticipation of the final position once the first (or second) target stimulus was shown. Thus, it seems unlikely that representational momentum is a phenomenon that may extend to natural viewing of moving objects because many natural motion sequences tend to be even less predictable. Typically, natural motion cannot be viewed repeatedly, and our prediction of the motion of a subsequently viewed object are typically not based on our just having witnessed an identical motion. In this very limited scope, however, the notion of dynamic mental representations loses much of its appeal. Functionally, the dynamic nature of mental representations was supposed to be of relevance for motor interactions with the environment. It was assumed that the mental extrapolation of moving objects would help observers to guide their movements towards those objects (e.g., Freyd & Johnson, 1987). However, a mechanism that relied heavily on repeated presentation of the motion-to-be-intercepted would hardly serve that purpose.

Perceptual processes

An alternative view of the localization error assumes that expectations resulting from highly predictable target behaviour may influence perceptual processes. In particular, expectations may influence eye movements or attention shifts. Recently, eye movements were found to strongly influence localization of the final position of targets moving smoothly on linear trajectories. Kerzel et al. (in press) showed that the observer's gaze overshoots the final position of a moving target that disappears at a random position along its trajectory. Under these conditions, both the direction of gaze, and the judged final position were shifted in the direction of motion, which is consistent with the hypothesis that observers have a tendency to localize objects toward the fovea. When the overshoot of the eyes was suppressed by instructing observers to maintain fixation, the forward displacement was eliminated (for a similar finding, see Whitney & Cavanagh, this issue; for conflicting findings, see Müsseler, Stork, & Kerzel, this issue). Further, when the target disappeared at a predictable turning point, the eyes did not overshoot the final position to the same degree as with a random vanishing point. Apparently, observers anticipated the reversal and slowed down their pursuit eye movements, such that the overshoot decreased. Analogous to the movements of the eyes, forward displacement was found to be reduced or even reversed at these locations (Hubbard & Bharucha, 1988). Thus, eye movements and localization behaviour are correlated. Additionally, eye movements may combine with low-level processes to produce mislocalization on a very small time scale. Kerzel (2000a) found that the visible persistence of a black target on a white background was on the order of 50 to

60 ms. That is, for a brief time after target offset, the neural response related to the target stimulus continued. If eye movements occur during this time interval, the observer will actually see a target at a position that deviates from its physically final position. Thus, if an eye movement occurs in the direction of motion, the observer will see the target to be displaced in that direction.

In the present study, expectations of the observer that resulted from high target predictability may have influenced eye movements. A sequence of implied motion took at least 1474 ms. It is highly probable that shifts of fixation occurred, given that saccades occur about 3–4 times per second under natural viewing conditions. As the localization error was relatively small, even very small shifts may have strongly altered the results. For instance, a mislocalization of 3.4° of rotation (the standard forward shift in condition BS-DR + F-FP) translates into a mislocalization of 0.22° of visual angle for one of the corner dots at 3.9° from fixation. Thus, if an eye movement occurred while the image of the stimulus persisted (about 50 ms after offset), a very small shift would suffice to introduce an error in localization. In fact, the shift could be smaller than what is customarily considered fixation (1° of visual angle, e.g., Müsseler & Aschersleben, 1998). For instance, in some trials observers may have tracked parts of the rectangle by saccades. It is known that saccades often undershoot their final destination (by about 10%) and a corrective second saccade is required (Becker & Fuchs, 1969). If the corrective saccade occurred during the RI, a shift of the persisting image was produced. Similarly, postsaccadic drift (Kapoula, Robinson, & Hain, 1986) into the direction of implied motion may produce such a distortion. Also, presenting the same direction of rotation throughout the experimental session may have induced observers to return to previous target positions after the final target presentation. If gaze was directed at previous target positions, a backward shift is expected because objects are localized towards the fovea (Kerzel, 2000a).

In the present study, perceptual confounds were most likely to be eliminated in the condition in which both DR and FP varied randomly. In this condition, observers were unable to form strong expectancies about the future trajectory of the target. Without prior knowledge about where the target will appear, or disappear, or in which direction the target will rotate, eye movements and attention shifts are less likely to be systematic. This condition was realized in WS-DR + R-FP. For theories of representational momentum, it is damaging to find that the forward shift is eliminated in this condition as it is the condition that renders perceptual accounts (Kerzel, 2000a,b; Kerzel et al., in press) less likely.

In sum, the present data suggest that expectations building up across trials strongly influence the size and the time course of the forward shift. Therefore, current theories of representational momentum have to be restricted in the sense that mental continuation with implied motion only occurs with strong expectations about a target's motion. Alternatively, one may assume that perceptual processes influence, if not cause, the forward shift.

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