Illusory motion and representational momentum

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When a moving target vanishes abruptly, participants judge its final position as being ahead of its actual final position, in the direction of motion (*representational momentum*; Freyd & Finke, 1984). In the present study, we presented illusory motion and examined whether or not forward displacement was affected by the perceived direction and speed of the target. Experiments 1A and 1B showed that an illusory direction of movement of a target was perceived, and Experiment 2 showed that an illusory speed of a moving target was observed. However, neither the direction nor the magnitude of forward displacement was affected by these illusions. Therefore, it was suggested that the mechanism underlying forward displacement (or some extrapolation processing) uses different motion signals than does the perceptual mechanism.

When a moving target vanishes abruptly, observers asked to judge its final position place it ahead of its actual final position, in the direction of its motion. An early explanation of this forward displacement originated from the similarity between the physical momentum of a moving object and momentum in the visual representational system (Freyd & Finke, 1984). A physical object in motion cannot stop immediately, but coasts for some distance. Similarly, it was assumed that an observer's mental representation of an object in motion acquires a momentum-like character and cannot stop immediately. On the basis of this similarity, the observed forward displacement was called *representational momentum*.

It has been found that a number of variables influence forward displacement (for a review, see Hubbard, 1995b). Forward displacement increases with the speed (see, e.g., Freyd & Finke, 1985; Hubbard & Bharucha, 1988) and acceleration (Finke, Freyd, & Shyi, 1986) of the moving target. These findings suggested a similarity between forward displacement and physical momentum. Subsequently, Hubbard and others demonstrated that forward displacement reflects physical principles. For example, forward displacement increases in the direction of gravity (see, e.g., Hubbard, 1990, 1995a, 1997; Hubbard & Bharucha, 1988; Nagai, Kazai, & Yagi, 2002), whereas it is reduced by implied friction between a moving stimu-

lus and an adjoining surface (Hubbard, 1995a; see also Nagai & Yagi, 2001). Moreover, forward displacement is influenced by real-world knowledge of the typical motions of familiar objects (see, e.g., Reed & Vinson, 1996; Vinson & Reed, 2002; but see also Nagai & Yagi, 2001) and the future trajectory of a target (Hubbard & Bharucha, 1988; Verfaillie & d'Ydewalle, 1991). Although the mechanism underlying forward displacement remains controversial (Finke & Freyd, 1989; Finke et al., 1986; Hubbard, 1995b, 1998, 1999; Kelly & Freyd, 1987; Kerzel, 2000, 2002; Munger & Minchew, 2002; Nagai et al., 2002), it is agreed that some extrapolation process is involved in the production of forward displacement. In other words, forward displacement is assumed to be produced by the continuation or extrapolation of an object's past trajectory beyond its actual final position, through the use of some mental calculation or guidance of eye movements.

Note that in the studies cited above it was implicitly assumed that the motion of the target was correctly perceived while the target was visible, but this was not confirmed. For example, Hubbard and Bharucha (1988) showed that a target's rightward motion elicited downward as well as forward (i.e., rightward) displacement, although there was no downward component in the target's motion. This assumption suggested that the influence of gravity occurred not in the perception of motion but in the underlying mechanism of forward displacement (or some extrapolation process). However, it is also possible that the target was perceived incorrectly (i.e., as moving down to the right) or that the influence of gravity was present solely in the perceptual system. In this case, the underlying mechanism used just such perceived motion of the target and extrapolated the position of the target accordingly, so that gravitation influenced forward displacement. It is unclear which of these two possibilities is the case, because previous studies have not confirmed whether forward displacement is produced by extrapolating the *perceived* or the *veridical* motion of a

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target. The concept of *illusory motion* is useful for addressing this issue, because it explicitly makes the distinction between the perceived motion and the veridical motion of a target. By presenting illusory motion, in the present study we dissociated the perceived motion of a target from its veridical motion and investigated whether forward displacement followed its perceived or its veridical motion.

The best-known example of illusory motion is the Duncker (1937) illusion (also known as *induced motion*). When a moving frame is presented as a context surrounding a stationary target, observers perceive the stationary target as moving in the direction opposite the motion of the context. Swanson (1984) found that the perceived path of a target moving horizontally was displaced vertically when the target crossed contextual inclined lines. In his examples, either a target or a context moved but the other element was stationary. Illusory motion still occurred in the case in which both elements moved. Wallach, Bacon, and Schulman (1978) presented a frame (context) moving horizontally back and forth and a dot (target) moving vertically back and forth. The frame and the dot changed their directions of motion simultaneously. Observers perceived the dot to be moving along a diagonal path rather than along the physical (vertical) path. Illusory motion was also observed in the domain of speed perception when a moving textured background was used (Raymond, Shapiro, & Rose, 1984). For example, when a background of scattered dots moved in the same direction as a target, it was perceived to move at a slower speed than its veridical speed. In contrast, when the background moved in the opposite direction of a target, it was perceived to move at a faster speed than its veridical speed.

In this study, we presented a moving context or background that caused illusory motion of a moving target. In Experiments 1A and 1B, the target moved diagonally in a zigzag pattern and the context moved to the right in line with the target along the vertical axis (Johansson, 1973, showed a similar example). In this display, participants were expected to perceive that the target moved almost vertically rather than in its physical direction of motion. In Experiments 1A and 1B, we examined whether forward displacement occurs in the perceived direction of a target's motion or in the physical direction. In Experiment 2, a target moved rightward at one of several speeds in each trial. A background of dots moved leftward, rightward, or not at all, which modulated the perceived speed of the target. In Experiment 2, we tested whether the perceived and/or the veridical speed of the target influenced forward displacement.

EXPERIMENT 1A

In Experiment 1A, a target (a black disc) moved down to the right, up to the right, and down to the right in the first, second, and test phases, respectively. In the target-only condition, only the target was presented, whereas in the context condition, two black discs were also pre-

sented as context. The context moved to the right in line with the target along the vertical axis. The target and context disappeared simultaneously in the test phase. In the context condition, the participants were expected to perceive illusory motion of the target. The participants were asked to perform one of two tasks in each trial: to judge the direction of the target's motion in the test phase, or to judge its final position. With these stimuli and tasks, we investigated whether illusory motion affected forward displacement.

Method

Participants. Three graduate students at Kyoto University and 9 undergraduate students at Kyoto Koka Women's University were each paid 1,000 yen (about \$9) for their participation. All the participants had normal or corrected-to-normal vision. They were naive as to the purpose of the experiment.

Apparatus. Stimuli were presented on a 21-in. CRT monitor (Iiyama S103M) controlled using a Macintosh G4/466 computer. The monitor had a refresh rate of 85 Hz and a spatial resolution of $1,600 \times 1,200$ pixels; it was placed 57.3 cm from the participant's eyes. The participants' responses were input into the computer with a mouse.

Materials. The target was a black disc with a diameter of 0.48° (20 pixels) in visual angle, which appeared on a white background. The target appeared 0.71° (30 pixels) to the right of the left edge of the screen and 11.43° (480 pixels) below the upper edge, and then moved down to the right (first phase), up to the right (second phase), and down to the right (test phase), as is shown in Figure 1. The movement of the target deviated from the horizontal axis in one of five directions: 27° , 37° , 45° , 53° , or 63° . The target position was updated on each screen refresh. With the 27° deviation direction, the target position was updated horizontally (rightward) by 4 pixels and vertically (upward in the first and test phases, downward in the second phase) by 2 pixels. The combinations of these values (horizontal, vertical) are (4, 3) at 37° , (3, 3) at 45° , (3, 4) at 53° , and (2, 4) at 63° . The vertical length of the target's path was fixed at 5.71° (240 pixels) in all deviated directions (as will be described later, in the test phase the target disappeared before it traveled the full length of its path). Thus, the shallower the deviation direction, the longer the path length of a moving target would be.

In the first and second phases, the directions of the target were randomly selected from the five deviated directions in each trial. In the test phase, the direction of the target was also selected from the five deviated directions, but only the data for 27° , 45° , and 63° were analyzed (the probability of presentation of each of these directions was 28.6%). Note that the target's speeds in these directions were similar (8.94° , 8.49° , and $8.94^\circ/\text{sec}$, respectively). The other directions of motion (37° and 53°) were presented as fillers and were not analyzed (the probability of presentation of each filler direction was 7.1%). The point of using two filler directions was to make the participants less likely to predict the direction of a moving target in the test phase. The main reason that the filler direction data were not analyzed was that the target's speed in the filler direction ($10^\circ/\text{sec}$ in both deviation directions) was at least 11.9% greater than its speed in the other, to-be-analyzed directions. To better control the present experiment, the difference in the unmanipulated factor—speed—should be minimized in the to-be-analyzed directions.

In the context condition, two black discs, of the same size as the target, were also presented. The context moved rightward in line with the target along the vertical axis. The distance between the two black discs was always 7.62° (320 pixels). When the target was in the uppermost or lowermost position, the distance between the target and one element of the context was 0.98° (42 pixels). The speed of the context was not constant across the three phases and changed with the horizontal speed component of the target's motion. The

Figure 1. (A) The stimuli used in Experiment 1A. Solid circles represent the moving target and context, and open circles represent possible final positions of the target. In the target-only condition, only the target was presented. In the context condition, context was also presented, and the context and target vanished simultaneously. The direction of deviation of the target from the horizontal axis was randomly chosen from five possible directions. In this example, the target moved at 63° in the first phase, at 27° in the second phase, and at 45° in the test phase. After the target (and context) vanished, the indicator for direction judgment or the “+” cursor for final position judgment was presented. (B) Explanation of the deviation and magnitude of forward displacement. The solid circle represents the true final position of a moving target, and the open circles (1 and 2) represent two examples of the judged final position of the moving target. Shown is an example of the target’s moving at 63° in the test phase. Judged Final Position 1 shows negative magnitude of forward displacement (i.e., backward displacement) and positive deviation of forward displacement (i.e., steeper deviation). Judged Final Position 2 shows positive magnitude of forward displacement (i.e., forward displacement) and negative deviation of forward displacement (i.e., shallower deviation). Note that the two examples have the same absolute magnitude of forward displacement but different signs and different sizes of deviation (i.e., the steeper deviation is larger than the shallower deviation).

context and target vanished simultaneously. In the test phase, the target vanished at one of three positions. As is shown in Figure 1, the target vanished after traveling one, two, or three quarters of the path length in the test phase. We did not use the turning point of the target as its final position because at this position the target and one of the black discs were close together, so the position of the context might have affected the judged final position of the target (the landmark effect; Hubbard & Ruppel, 1999).¹

In both conditions, immediately after the target vanished a crosshair cursor (for final position judgments) or a pointer (for direction judgments) was presented. The participants could never predict which task they would be asked to perform because of the random selection of the crosshair cursor or the pointer. The cursor was presented at a random position within a $2.38^\circ \times 2.38^\circ$ (100×100 pixel) region located at the center of the screen. The center of the pointer was 9.52° (400 pixels) below the center of the upper screen edge. The pointer's arm was 1.90° (80 pixels) long. The direction of the pointer's arm was randomly set in the right half of the arc.

Procedure. One of two tasks was randomly selected in each trial: judging either the final position of the target or judging the direction of its motion. When the crosshair cursor was presented, the participants were asked to locate the final position of the moving target with the mouse cursor. When the pointer was presented, they were required to adjust it to the direction in which the target was traveling at the time when it vanished. The participants manipulated the cursor and pointer by moving the mouse. In both tasks, the participants were instructed to respond as quickly as possible but to maintain a high degree of accuracy. Note that in each trial the participants had to pay attention to both the direction of movement and the final position of a moving target, because it was impossible to know which task they would be asked to perform. No specific instructions on eye movements were given to the participants.

Each participant performed 168 trials. The experimental (to-be-analyzed) trials involved 2 tasks $\times$ 2 conditions $\times$ 3 final positions of the moving target $\times$ 3 directions of the moving target in the test phase $\times$ 4 replications; the filler (not-to-be-analyzed) trials involved 2 tasks $\times$ 2 conditions $\times$ 3 final positions of the moving target $\times$ 2 directions of the moving target in the test phase.

The participants initiated each trial by clicking on the mouse. Trials were divided into six blocks of 28. Two conditions and two types of trial were intermixed in each block. After familiarizing themselves with the rotation of the pointer for the direction judgment, the participants performed one or two blocks as practice. One block of practice was enough for most of the participants to familiarize themselves with the tasks, but a few needed to perform one more block before they were confident about doing the tasks. No error feedback was given throughout the entire session, which lasted about 50 min.

Results

Direction judgment. In Figure 2A, the mean judged direction of the target's motion is shown as a function of the physical direction of the target's motion in the test phase. The judged direction was represented as the angular deviation from the horizontal axis. Thus, if the judged direction were exactly the same as the physical direction of the target's motion, the plots in Figure 2A would lie on a diagonal line (bottom left to top right). Each plot was created by collapsing the data over the three path lengths in the test phase. The judged directions were analyzed for a 2 (condition) $\times$ 3 (direction of movement in the test phase) repeated measures analysis of variance (ANOVA). The main effects of condition [$F(1,11) = 60.25$, $MS_e = 137.06$, $p < .0001$], direction of movement [$F(2,22) = 84.29$, $MS_e = 26.58$, $p < .0001$],

Figure 2. The data on judged direction and forward displacement in Experiment 1A. (A) The judged directions of a target's motion in the target-only (open circles) and context (filled squares) conditions. (B) The deviations of forward displacement in both conditions. (C) The magnitudes of forward displacement in both conditions. Error bars indicate standard errors of the means. Note that the units in panel A represent degree of rotation, whereas those in panels B and C represent degree of visual angle.

and their interaction [$F(2,22) = 31.26$, $MS_e = 31.26$, $p < .0001$] were significant. This confirmed that there was a significant difference in the judged direction of the target's motion between the target-only and the context conditions.

Forward displacement. The data of forward displacement were analyzed in two dimensions: its deviation and its magnitude (Figure 1B). The deviation of forward displacement was defined as a signed distance between the judged final position and the extended line of the target's direction of movement in the test phase. In order to discriminate steeper and shallower deviations from the true direction of movement of the target, the extended line of the target's direction of movement in the test phase served as the *border for deviation*. A positive sign was assigned to the deviation of forward displacement in the case in which the judged final position was on the *steeper* side of the border for deviation (e.g., Judged Final Position 1 in Figure 1B). In contrast, the negative sign was assigned to the deviation of forward displacement in the case in which the judged final position was on the *shallower* side of the border for deviation (e.g., Judged Final Position 2). The magnitude of forward displacement was calculated in a similar manner. It was defined as a signed distance between the judged final position and the border for magnitude. The border for magnitude was the line that was perpendicular to the target's direction of movement in the test phase and that passed through the target's true final position. A positive sign was assigned to the magnitude of forward displacement in the case in which the judged final position was beyond the border in the direction of the target's motion (e.g., Judged Final Position 2). In contrast, a negative sign was assigned to the magnitude of forward displacement in the case in which the judged final position was behind the border (i.e., backward displacement, as in the example of Judged Final Position 1).

In Figure 2B, the mean deviation of forward displacement is shown as a function of the physical direction of the target's motion in the test phase. Each plot in Figure 2B resulted from collapsing the data over the three path lengths in the test phase. The deviations of forward displacement were analyzed in a 2 (condition) $\times$ 3 (direction of movement in the test phase) ANOVA. The main effects of direction of movement, condition, and their interaction were not significant. Unlike the direction judgment, there was no difference in the deviation of forward displacement between the two conditions.

In Figure 2C, the mean magnitude of forward displacement is shown as a function of the physical direction of the target's motion in the test phase. Each plot was created by collapsing the data over the three path lengths in the test phase. First, we examined whether the magnitude of forward displacement was significantly larger than zero. The t tests revealed that forward displacement for all of the target's motions in both conditions was significantly larger than zero [all $t_s(11) > 2.90$, all $p_s < .014$], confirming that forward displacement occurred in all of the target's motions. Second, we examined whether or not the magnitudes of forward displacement were the same in the two conditions. The magnitude of forward displacement was analyzed in a 2 (condition) $\times$ 3 (direction of movement in the test phase) ANOVA. The

main effect of direction of movement [$F(2,22) = 8.84$, $MS_e = 138.24$, $p < .01$] and the interaction between condition and direction of movement [$F(2,22) = 4.17$, $MS_e = 111.35$, $p < .05$] were significant; the main effect of condition [$F(1,11) = 4.51$, $MS_e = 39.72$, $p = .057$] was marginally significant. For the significant interaction, we performed post hoc Tukey's HSD tests ($p < .05$), which focused on the differences in the magnitude of forward displacement for each direction of movement between the conditions. The tests revealed no difference and confirmed that the magnitude of forward displacement did not differ between conditions.

Discussion

The data for direction judgment showed a significant difference between the conditions. This suggests that the participants perceived the path of the target's motion as steeper in the context condition than in the target-only condition; thus, illusory motion of the targets was observed in the context condition. By contrast, the data on the deviations and magnitude of forward displacement did not differ between conditions. This suggests that forward displacement was not affected by the perceived or illusory motion of the targets.

Broadly speaking, the magnitude of forward displacement decreased as the physical direction of the target's motion increased (Figure 2C). This trend was consistent with the finding that the horizontal motion of the target yielded larger forward displacement than did its vertical motion (Hubbard, 1990). Although the statistical tests did not support it, there is clear drop at 45° of the target's direction of movement in the context condition. We have no clear explanation for this trend, but it might be due to some unexpected bias derived from using just the lower right direction of movement of the target in the test phase.

EXPERIMENT 1B

In Experiment 1A, we used only the target's motion toward the lower right in the test phase. This fixed direction of motion in that phase might have led to a gravitational bias in forward displacement (see, e.g., Hubbard & Bharucha, 1988) or to some unexpected biases. Therefore, in Experiment 1B the target's motion toward the upper right was also presented in the test phase, and a similar experiment was conducted.

Method

Participants. Four graduate students at Kyoto University and 10 students (9 undergraduate and 1 graduate) at Kyoto Koka Women's University were each paid 1,000 yen (about \$9) for their participation. All the participants had normal or corrected-to-normal vision. They were naive as to the purpose of the experiment.

Apparatus. The apparatus was the same as that used in Experiment 1A.

Materials. In half of the trials, the target appeared, as in the previous experiment, 0.71° (30 pixels) to the right of the left edge of the screen and 11.43° (480 pixels) below its upper edge and then moved in one of five directions down to the right (first phase), up to the right (second phase), and down to the right (test phase). In the

other half of the trials, the target appeared 0.71° to the right of the left edge of the screen and 11.43° above its lower edge and then moved in one of five directions up to the right, down to the right, and up to the right. The initial position was selected semirandomly from these two. In the test phase, the target vanished after it had traveled one third or two thirds of the whole path in the test phase. The other stimulus settings were the same as in Experiment 1A.

Procedure. The task and procedure were the same as in Experiment 1A, except for the following points. Each participant performed 208 trials: The experimental (to-be-analyzed) trials involved 2 tasks $\times$ 2 conditions $\times$ 2 onset positions for the target $\times$ 2 final positions for the moving target $\times$ 3 directions of the moving target in the test phase $\times$ 4 replications; the filler (not-to-be-analyzed) trials involved 2 tasks $\times$ 2 conditions $\times$ 2 final positions of the moving target $\times$ 2 directions of the moving target in the test phase. The experiment was divided into eight blocks of 26 trials. The entire session lasted about 60 min.

Results

Direction judgment. As is shown in Figure 3A, the data for judging direction were similar to those in Experiment 1A. The judged directions were analyzed in a 2 (condition) $\times$ 3 (direction of movement in the test phase) ANOVA. The main effects of condition [$F(1,12) = 56.77$, $MS_e = 157.47$, $p < .0001$], direction [$F(2,24) = 46.71$, $MS_e = 45.20$, $p < .0001$], and their interaction [$F(2,24) = 18.69$, $MS_e = 20.45$, $p < .0001$] were significant. This confirmed that there was a significant difference in the judged direction of the target's motion between the target-only and context conditions.

Forward displacement. Figure 3B shows the data for the deviation of forward displacement. The deviation of forward displacement was analyzed in a 2 (condition) $\times$ 3 (direction of movement in the test phase) ANOVA. The main effects of direction of movement, condition, and their interaction were not significant. Unlike in the case of direction judgment, there was no difference in the deviation of forward displacement between the two conditions.

Figure 3C shows the data for the magnitude of forward displacement. The t tests revealed that forward displacement for all the target's motions in both conditions were significantly larger than zero [all $t_s(12) > 4.67$, all $p_s < .001$]. This confirmed that forward displacement occurred in all the target's motions. The magnitudes of forward displacement were analyzed in a 2 (condition) $\times$ 3 (moving) direction in the test phase ANOVA. The main effects of condition, direction of movement, and their interaction were not significant. This confirmed that there was no difference in the magnitude of forward displacement between the conditions.

Discussion

As in Experiment 1A, the data for direction judgments differed significantly between the two conditions whereas the data for the deviation and magnitude of forward displacement did not differ between the conditions. This suggests that forward displacement was not affected by the perceived or illusory motion of the target. The replication of Experiment 1A supports our present findings.

Unlike in Experiment 1A, the statistical tests in Experiment 1B clearly indicate that there was no difference in

Figure 3. The data on judged direction and forward displacement in Experiment 1B. (A) The judged directions of a target's motion in the target-only and context conditions. (B) The deviations of forward displacement in both conditions. (C) The magnitudes of forward displacement in both conditions. Error bars indicate standard errors of the means. Note that the units in panel A represent degree of rotation, whereas those in panels B and C represent degree of visual angle.

the magnitude of forward displacement between the two conditions. This is due to the proper control of the stimulus setting, achieved by using the target's motions in both the upper right and lower right directions in the test phase.

EXPERIMENT 2

Experiments 1A and 1B showed that the judged direction of the target's motion was affected by illusory motion, but forward displacement was not affected. For further support of the present finding, in Experiment 2, we used a background motion of scattered dots to produce illusory motion (Figure 4). A target moved rightward at one of several speeds in each trial. The background moved leftward, rightward, or not at all. When the background moved rightward, the target was perceived to move at a slower speed than its veridical speed. In contrast, when the background moved leftward, the target was perceived to move at a faster speed than its veridical speed. This experiment was a test of whether the perceived or the veridical speed of the target influenced forward displacement.

Method

Participants. One of the authors and 8 undergraduate and graduate students at Kyoto University and Kyoto Koka Women's University participated in this experiment. The students were each paid 1,000 yen (about \$9) for their participation. All the participants had normal or corrected-to-normal vision. They were naive as to the purpose of the experiment.

Apparatus. The apparatus was the same as in that used in Experiments 1A and 1B.

Materials. The target was a black disc on a white background, and its diameter was 0.50° (21 pixels). The target moved rightward at one of eight speeds: 4.94° , 6.92° , 7.90° , 8.89° , 10.87° , 11.86° , 12.85° , or $14.82^\circ/\text{sec}$ (207, 290, 332, 373, 456, 498, 539, or 622 pixels/sec).

Figure 4. The stimuli used in Experiment 2. The solid circle represents the moving target. The target moved rightward at one of eight speeds on each trial. Small, scattered dots represent a background. They moved rightward, leftward, or not at all. The target and background appeared and vanished simultaneously. After the target and background vanished, the scale for speed estimation or the "+" cursor for final position judgment was presented.

In the test (to-be-analyzed) trials, the speed of the target was either $7.90^\circ/\text{sec}$ or $11.86^\circ/\text{sec}$ and the target vanished at one of five positions: the screen center, 1.14° (48 pixels) to the left or to the right of the center, or 2.28° (96 pixels) to the left or to the right of the center. In the rest of the trials (not-to-be-analyzed, filler trials), the speeds of the target were 4.94° , 6.92° , 8.89° , 10.87° , 12.85° , and $14.82^\circ/\text{sec}$ and the target vanished at one of five positions that were slightly different from those in the test trials. The point of using filler trials was to make the participants less likely to predict the speed of the moving target in each trial. The number of repetitions of each speed in the filler trials was smaller than that in the test trials, and the number of filler trials was too small to be reasonably analyzed (for the data of the filler trials to be reasonably analyzed, 2.8 times more trials would be needed). Therefore, the data of filler trials were not analyzed. When the target vanished at the leftmost position, the duration of the target presentation was 706 msec irrespective of type of trial. This means that the starting position of the target's motion depended on its speed. In the test trials, when the target vanished at the rightmost position, the duration of the target was 1,284 msec for its slower speed ($7.90^\circ/\text{sec}$) or 1,092 msec for the faster one ($11.86^\circ/\text{sec}$). In the filler trials, these durations ranged from 1,014 to 1,631 msec.

A background of randomly scattered dots (each $0.10^\circ \times 0.10^\circ$, or 4×4 pixels, and 4% density) in a rectangular area of $38.10^\circ \times 7.14^\circ$ ($1,600 \times 300$ pixels) in the vertical center of the screen were also presented in every trial. The background was stationary or it moved either in the same direction as the target's motion (i.e., rightward) or in the opposite direction (i.e., leftward). The scattered dots moved 100% coherently. When the background moved, their speed was $5.93^\circ/\text{sec}$ (249 pixels/sec). The background appeared and vanished at the same time as the target did.

Task. After the offset of the stimuli, either a crosshair cursor or a scale for magnitude estimation of the target speed was randomly selected and presented in each trial. Forty-seven milliseconds after the offset, the cursor appeared at a random position within a $0.98^\circ \times 0.98^\circ$ (42×42 -pixel) region located at the center of the screen. One hundred eighteen milliseconds after the stimuli's offset, the scale—a vertical line divided into four equal lengths by short horizontal lines—appeared.² The participants could not predict whether the cursor or the scale would be presented. Therefore, the participants were required to pay attention to both the target's speed and its final position in each trial. When the cursor appeared, they were asked to indicate where the target had vanished. When the scale appeared, their task was to indicate the speed of the target on that scale (magnitude estimation technique; Stevens, 1975).

The scale had 200 points; the value 0 (labeled "slow" on the screen) corresponded to the slowest judged speed, and the value 200 (labeled "fast" on the screen) corresponded to the fastest judged speed. The participants were instructed to use the full range of this scale.

Procedure. Each participant performed 252 trials. The test (to-be-analyzed) trials involved 2 tasks $\times$ 2 speeds $\times$ 3 background motions $\times$ 5 final positions $\times$ 3 replications; the filler (not-to-be-analyzed) trials involved 2 tasks $\times$ 6 speeds $\times$ 3 background motions $\times$ 2 final positions, randomly chosen from the five. The experiment was divided into 12 blocks of 21 trials. Two practice blocks preceded the experimental trials. No feedback was provided throughout the entire session. As in the previous experiments, no specific instructions on eye movements were given to the participants. The entire session lasted about 60 min.

Results

Speed estimation. In Figure 5A, the mean estimated target speed is shown as a function of the physical speed of the target's motion. The data for each plot are collapsed over five final positions of the target. The data

were analyzed in a 2 (speed) $\times$ 3 (background motion) ANOVA. Significant main effects for speed [$F(1,8) = 268.43, p < .001$] and for background motion [$F(2,16) = 52.63, p < .001$] were found, and their interaction was marginally significant [$F(2,16) = 2.98, p = .079$].

Forward and vertical displacement. Unlike in the first two experiments, in the present experiment the physical and perceived speeds of the target were manipulated. Since the horizontal (or rightward) target motion was used, the effect of speed should appear in the magnitude of forward displacement along the horizontal axis. As in previous studies using horizontal motions with the cursor-pointing response (e.g., Hubbard, 1990; Hubbard & Bharucha, 1988), forward displacement data were divided into horizontal and vertical components. The horizontal component of displacement was displacement along the target's motion path (referred as M displacement in the previous studies). This horizontal component of displacement was equivalent to forward displacement. If the judged final position of the target shifted in the direction of motion (i.e., rightward), a positive sign was assigned to the magnitude of forward displacement. If the judged final position shifted in the opposite direction of the target's motion (i.e., leftward), the magnitude of forward displacement was assigned a negative sign (i.e., backward displacement). The vertical component of displacement was displacement along the axis orthogonal to the target's motion path (referred to as O displacement in the previous studies). As in the previous studies, a positive sign was assigned to upward displacement and a negative sign was assigned to downward displacement.

In Figure 5B, the mean magnitude of forward displacement is shown as a function of the physical speed of the target's motion. The data for each plot are collapsed over five final positions of the target. The t tests revealed that forward displacement for all the target's speeds with all background motions was significantly greater than zero [all $t_s(8) > 3.84$, all $p_s < .01$]. This confirmed that forward displacement occurred in all the target's motions. The horizontal magnitude of forward displacement was analyzed in a 2 (speed) $\times$ 3 (background motion) ANOVA. A significant main effect for speed [$F(1,8) = 9.34, p < .05$] and a significant speed $\times$ background interaction were found [$F(2,16) = 3.77, p < .05$]. However, a main effect for background motion was not significant [$F(2,16) < 1$].

In Figure 5C, the mean magnitude of vertical displacement is shown as a function of the physical speed of the target's motion. The data for each plot are collapsed over five final positions of the target. The t tests revealed that downward displacement for all the target's speeds with all background motions was larger than zero at marginally significant levels [$1.86 < \text{all } t_s(8) < 2.29$, $.05 < \text{all } p_s < .10$]. This suggests that downward displacement, or gravity effect on forward displacement (see, e.g., Hubbard, 1990, 1995a, 1997; Hubbard & Bharucha, 1988; Nagai et al., 2002), occurred in all the target's motions. Note that in the present experiment the

Figure 5. The results of Experiment 2. (A) Estimated speed of the target's motion. (B) The magnitude of forward displacement along the horizontal dimension. (C) The magnitude of vertical displacement. Negative values mean downward displacement. Error bars indicate standard errors of the means. In panel C, standard errors were smaller than the size of the symbols.

speeds of the horizontal target motions were manipulated and the speed of the vertical target motion was zero. Thus, it was expected that there would be no influence of the horizontal speed manipulation on vertical displacement. As was expected, a 2 (speed) $\times$ 3 (background motion) ANOVA did not show any main effects or any interaction.

Discussion

The data for the speed estimation showed that the perceived speed of the target increased with the physical target's speed and was affected by the background motion. The target was perceived to move faster than its veridical speed when the background moved in the direction opposite the movement of the target, and it was perceived to move at a slower speed than its veridical speed when the background moved in the same direction as the target. Therefore, it was confirmed that illusory motion occurred. In contrast, the magnitude of forward displacement increased with the target's physical speed, but it was not affected by the target's illusory speed. The significant interaction in the magnitude of forward displacement would reflect whether or not the background moved (Figure 5B). In other words, the magnitude of forward displacement is more sensitive to the target's physical speed in the case of a stationary background than in the case of a moving background. The marginally significant interaction in the speed estimation might reflect the same trend (Figure 5A). This trend was beyond the scope of the present study. However, we could suggest that weaker processing focus (e.g., less attention) on a target in the case of background motion might lead to weaker sensitivities to physical speed of motion. This might be possible, because it has been reported that attention modulates both the magnitude of forward displacement (Hayes & Freyd, 2002) and the perception of motion (for a review, see Raymond, 2000).

GENERAL DISCUSSION

Previous studies have not confirmed whether forward displacement is produced by extrapolating the perceived motion of a target or its veridical motion. In the present study, we attempted to dissociate the perceived motion of a target from its veridical motion by displaying illusory motion, and we investigated whether forward displacement was influenced by the illusion. Experiments 1A and 1B showed that the judged directions of the target's motion in the target-only condition were different from those in the context condition (i.e., illusory direction of motion was observed), but the deviation and magnitude of forward displacement for the target in both conditions did not differ from each other. In Experiment 2, the data for the speed estimation showed that the perceived speed of the target increased with the physical target's speed and was also affected by the background motion (i.e., illusory speed was observed). In contrast, the magnitude of forward displacement increased with the physical target's speed but was not affected by the illusory speed. In conclusion, forward displacement was not affected by perceived or illusory motion, investigated here in terms of illusory direction of movement and illusory speed.

Although several studies have shown the effect of illusory motion on position judgments (Faust, 1990; Sheth & Shimojo, 2000), it is less clear whether its effect on forward displacement was really investigated in these

studies, because their methods and procedures were not standard ones in forward displacement studies. Faust (1990) presented a stationary target with a moving rectangle and showed that judgment of the target's position shifted in the direction opposite the motion of the rectangle (i.e., the Duncker illusion took place). However, it was unclear whether the position judgment error Faust measured was forward displacement or some other judgment error, because in forward displacement studies a moving target is presented. Moreover, the percentage at which participants perceived an illusory motion of a stationary target was only 22%. There was another problem with his procedure. Because the position judgment and illusory motion judgment were executed in different experiments with different populations of participants, it was unclear whether the participants paid attention simultaneously to both the target's final position and its illusory motion. In other words, it was not certain whether the participants really perceived illusory motion in the position judgment experiment. Therefore, it was unclear whether Faust's finding on the position judgment was actually related to the perception of illusory motion. Finally, Faust found a very small magnitude of judged shift (only 0.3 pixels, corresponding to 0.03° of visual angle).

Sheth and Shimojo (2000) presented a moving target and motion of a background of randomly scattered dots (the direction of target motion was perpendicular to that of the background motion), and required participants to locate the initial and/or final position(s) of the target. The results showed that the final position judgment shifted in the direction of the illusory motion. The study of Sheth and Shimojo differed from the present study in instructions on eye movements. Their participants were required to fixate a fixation point throughout a trial. In contrast, our participants were not given specific instructions on eye movements and were likely to follow a moving target with their eyes (Kerzel, 2000). Several studies have shown that substantial magnitude of forward displacement is observed with pursuit eye movements for a moving target, but it is not observed or is greatly reduced with eye fixation (Kerzel, 2000; Thornton, 2002). Nevertheless, the magnitude of judged position error in Sheth and Shimojo was quite large (around 2.0°). Thus, it is unclear whether the position error they found was forward displacement or not. In the present experiments, we addressed the problems in Faust (1990) and tried to use a more standard procedure in forward displacement studies. In other words, a moving target was presented, eye movements were not limited, strong motion illusion was found, reasonably large forward displacement was found, and the judgments of direction of movement, speed, and final position were randomly selected on each trial in every block.

The present finding suggests that factors previously reported to influence forward displacement (e.g., physical principles, knowledge of objects' motions) might not do so in the perception system, but might produce forward displacement in an extrapolation mechanism. In

addition, our findings suggest that the direction judgment and the final position judgment use different information with regard to the target's motion, or that they are based on different modes of processing of motion information. In other words, the perception process produces the illusory motion of a target, but the visual system underlying forward displacement does not suffer from this and might use veridical motion information.

Note that our results do not suggest that forward displacement is based on on-line extrapolation using the veridical motion signals of a moving target, because forward displacement is measured as the response after the target disappears. In other words, forward displacement may be partially or exclusively based on the *off-line* processing of the position of a moving target. Concerning this point, Smeets and Brenner (1995)³ presented interesting data on on-line extrapolation processing when participants perceived illusory motion. First, they reported findings similar to ours. The perceived direction of a moving target was influenced by the illusory motion, but forward displacement was not affected by the illusory motion. They also examined the trajectory of manual hitting of the target and the position hit. The results suggested that the initial trajectory was affected by the illusion or that manual movement was diverted in the direction of the perceived or illusory motion. However, such a diversion was gradually corrected as the hitting movement proceeded, and the moving target was hit successfully. Since there is substantial delay from visual input to the execution of the hitting movement, it is assumed that the on-line hitting movement reflects on-line predictive and extrapolative processing. Therefore, these findings suggest that the on-line extrapolation mechanism in the early phase of hitting is affected by the visual illusion, whereas in its later phase it can utilize a veridical motion signal and predict the current veridical position of the moving target by canceling the transmission delay in the visual pathway, and can adjust the hand to the veridical current position of the moving target.

The final result of the manual hitting movement is consistent with our findings in suggesting that the underlying mechanism of forward displacement is not affected by illusory motions. However, our study of forward displacement does not show any data on the on-line extrapolation process. Although previous studies suggested that the underlying mechanism of forward displacement helps the on-line prediction of the future position of a moving object and allows for better regulation of bodily movements (Freyd & Johnson, 1987; Hubbard, 1995b; Nagai et al., 2002), there is no direct evidence from forward displacement studies that supports that idea. However, on-line extrapolation of the future position of a moving target could be partially related to the production of forward displacement. Future studies should examine the underlying extrapolation processing of forward displacement not just with forward memory displacement, but together with other measures reflecting on-line extrapolation processing, as in Smeets and Brenner (1995).

Finally, we point out one additional important difference between forward displacement and on-line manual pointing. As was discussed above, both forward displacement and manual pointing in its later phase utilize the same *direction* information in a target's motion (the veridical direction). However, they assess different *position* information. The data of Smeets and Brenner (1995) suggest that the underlying mechanism of manual pointing uses the veridical position information to enable successful hitting of the target. By contrast, the occurrence of forward displacement suggests that its underlying mechanism cannot utilize the veridical position information for the final position judgment.

We can present one possible explanation of forward displacement: It results from a timing error in the target's offset. The underlying mechanism of forward displacement can utilize the veridical direction and speed of a target's motion, but it cannot access the correct timing of the target's offset, and judges the timing to be later than the actual time. On the basis of such judged timing, the judged final position is calculated as if the target had traveled longer than is actually the case. As a result, it might be beyond the actual final position but along the veridical direction and at the veridical speed of the target's motion. Previous studies of forward displacement did not consider the judged timing of the target's offset.⁴ However, in other positional errors when a moving stimulus is presented (the Fröhlich effect and the flash-lag effect), the timing factor is a critical cause of these errors (Brenner & Smeets, 2000; Müller & Findlay, 1988; Murakami, 2001; Whitney & Murakami, 1998). A timing error explanation might also be possible in the case of forward displacement. Two findings in forward displacement are consistent with our explanation (Hayes & Freyd, 2002; Munger & Owens, 2004). Hayes and Freyd presented two moving targets, and participants were required to attend one of the targets. After the offset of targets, the participants were asked to judge the final position of either target. The magnitude of forward displacement for the unattended target was larger than that for the attended target. Munger and Owens showed that the magnitude of forward displacement was larger when another object was flashed at the offset of the moving target than when the flashed object was not added. In these studies, attention diverted away from the to-be-judged moving target caused slower processing of the timing of its offset, and thus the judged timing of offset could be even later than in the case in which the to-be-judged target was attended. Larger forward displacement for the unattended target is explained by the later judged timing of its offset.

In summary, in this study we dissociated the perceived motion of a target from its veridical motion by presenting illusory motion, and we showed that forward displacement is related to the veridical motion. This suggests that the underlying mechanism of forward displacement uses different motion signals than does the motion-perception mechanism.

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NOTES

1. A pilot experiment confirmed that the landmark effect did not occur when the deviated direction of the target was unpredictable and when the turning point of the target's direction was not used as its final position, as was the case in Experiments 1A and 1B.
2. In pilot experiments, we sought out the best interval for the two tasks and decided to use different intervals for the position (47 msec) and speed (117 msec) judgments. These were the shortest intervals that avoided the masking effect by the scale but afforded comfortable judgments in both tasks.
3. In one of Smeets and Brenner's (1995) experiments, a target disc moved in one of five directions (downward or in a direction diverted from perfectly downward to the left or to the right by 20° or 37°). Moreover, in an experimental condition, background texture motions were presented for producing illusory motion of the target. Participants were asked to judge the final position of the target or the direction of the target motion. Although their basic experimental design and results were similar to ours, there were several critical differences between the two studies. First, in Smeets and Brenner's study the two judgments were made in different experiments, whereas in the present study both judgments were made in every block. Thus, it was unclear whether the participants in their study really perceived illusory motion in the final position judgment experiment. Second, possibly because their main goal was to investigate reaching movement to a moving target, Smeets and Brenner did not show any statistical test of whether or not obtained

forward displacements were significant. Because of these points, the present paradigm was a better way to investigate the effect of illusory motion on forward displacement.

4. Although Freyd and Johnson (1987) found a temporal aspect of forward displacement (see also Hubbard, 1996), it was related to the memory process of the target's final position but not the judged timing, as we proposed here. In Freyd and Johnson's study, a probe judgment was used to estimate the magnitude of forward displacement, and participants were asked to respond whether the probe position was the same as or different from the target's final position. They found that forward displacement increased with the retention interval between target offset

and probe presentation with a short retention interval (up to 300 msec). Then, with a retention interval over 300 msec, it decreased as retention interval increased. They suggested that two memory processes (relatively short [up to 300 msec] and long [over 300 msec]) contributed to producing forward displacement. That study found a temporal aspect of forward displacement. However, their experiments did not address whether or not participants could access the true timing of target offset, and they did not discuss the judged timing issue.

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