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Conceptual influence on the flash-lag effect and representational momentum

MASAYOSHI NAGAI, MUTSUMI SUGANUMA, ROMI NIJHAWAN, JENNIFER J. FREYD, GEOFFREY MILLER, AND KATSUMI WATANABE

21.1 Introduction

When judging the position of a *moving* object, human observers do not perceive and memorize the moving object's correct position. There are two known phenomena in judged position errors of a moving object, representational momentum (RM) and the flash-lag effect (FLE), both of which we consider here.

RM was originally reported by Freyd and Finke (1984). Freyd and colleagues displayed a series of still frames to imply the rotation of a rectangle (e.g., Freyd & Finke 1984, 1985; Freyd & Johnson 1987). Observers saw three views of a rectangle at different rotations about its center, with 250 ms display duration with 250 ms interstimulus interval. The fourth rectangle was presented as a probe 250 ms after the third frame presentation. The rotation of the probe was selected from possible positions symmetrically distributed around the actual third position of rectangle. Observers were asked whether the rectangle in the third frame (the last frame of the motion sequence) was the same orientation as the probe. The results showed that their memory for the third orientation tended to be shifted in the direction of rotation. In other words, the orientation of the probe rectangle had to be rotated slightly further to be judged as being in the same position as the third rectangle. To account for the forward shift of the final position of a stimulus undergoing implied motion, some authors postulate that the dynamics of the representational system follow physical laws, such as momentum (representational momentum; RM Finke & Freyd 1985; Finke et al. 1986; Freyd 1987; Finke & Shyi 1988). RM is a robust effect as observed with smooth object motion and in pointing at the final position of a moving object (e.g., Hubbard & Bharucha 1988). Several variables influence RM (for review, Hubbard 1995b). RM increases with the velocity (e.g., Freyd & Finke 1985; Hubbard & Bharucha 1988; Nagai & Saiki 2005) and acceleration of the moving target (Finke et al. 1986), pointing to the similarity between RM and physical momentum. Hubbard and others demonstrated that RM may reflect physical principles. For example, RM increases downward, in the direction of gravity (Hubbard & Bharucha 1988; 1995a, 1997; Reed & Vinson 1996; Hubbard & Ruppel 1999; Nagai et al. 2002; Vinson & Reed 2002), whereas implied friction between a moving stimulus and an adjoining surface reduces RM (Hubbard 1995a; see also Nagai & Yagi 2001). Moreover, RM is influenced by real-world knowledge of the typical motions of familiar objects (Freyd

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& Miller 1992; Reed & Vinson 1996; Vinson & Reed 2002; but see Halpern & Kelly 1993; Nagai & Yagi 2001), the future or expected trajectory of a target (Hubbard & Bharucha 1988; Verfaillie & d'Ydewalle 1991), and visual attention (Hayes & Freyd 2002). Finally, Nagai and Saiki (2005) found that RM is elicited in the physical/actual direction and actual speed of an object's motion but not in its perceived direction and speed when the physical/actual versus perceived motions were different. Thus, a variety of factors affect RM: from low-level, perceptual factors such as a moving object's speed and acceleration to higher-level, cognitive factors such as expectation, attention, and each object's typical motion in the real world.

When a brief flash is presented adjacent to a continuously moving stimulus, the flash appears to lag behind the moving object. This flash-lag effect, FLE (Fröhlich 1923; Metzger 1932; Mackay 1958; Nijhawan 1994), is also robust and has been replicated in various stimulus configurations (Baldo & Klein 1995; Khurana & Nijhawan 1995; Nijhawan 1997; Kirschfeld & Kammer 1999; Brenner & Smeets 2000; Eagleman & Sejnowski 2000a; Khurana et al. 2000; Watanabe et al. 2001; Watanabe et al. 2003; Watanabe2004). Several factors are known to influence the FLE. The FLE increases as the luminance of the moving object is increased and decreases as the luminance of the flash is increased (Purushothaman et al. 1998). It increases as the retinal eccentricity of the flash is increased (Baldo & Klein 1995). Recently, Anstis (2007) found FLE occurs in the physical, not the subjective, direction of rotation. In addition to these low-level stimulus factors, perceptual grouping causes a large modulation of FLE magnitude (Watanabe et al. 2001; Watanabe 2004). FLE is reduced when the observer knows when and where the next flash is to occur (Brenner & Smeets 2000; Eagleman & Sejnowski 2000b; also see Nagai et al. 2000). Lastly, there is an ongoing debate about whether FLE is affected by attention (Khurana et al. 2000; Baldo et al. 2002). Thus, it is unclear whether the factors influencing FLE are limited to low-level or perceptual ones or also include higher cognitive factors similar to the factors affecting RM. Previously, it was shown that forward motion of objects that have a normal motion direction (e.g., animals that typically move headfirst) causes a larger RM effect than backward motion (Freyd & Miller 1992; Reed & Vinson 1996; Vinson & Reed 2002). Here we tested whether knowledge of an object's typical motion in the world influences FLE and directly compared it with that of RM. If such knowledge influences FLE, then forward motion would cause larger FLE than backward motion.

21.2 A flash-lag effect experiment

Here we tested the influence of object-typical motions on FLE. There were three different conditions: forward, backward, and stationary conditions (i.e., control condition). In the forward condition, the picture of a car moved forward, whereas in the backward condition it moved backward. In the control condition, the picture did not move. If the influence of object-typical motions exists in the FLE, then FLE in the forward condition should be larger than in the backward condition, as shown in RM studies (Freyd & Miller 1992; Reed & Vinson 1996; Vinson & Reed 2002).

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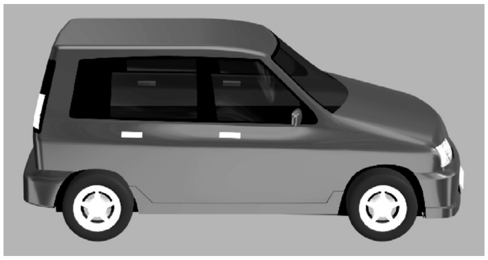

Fig. 21.1 An example of picture stimuli used in flash-lag experiment.

21.2.1 Method

21.2.1.1 Observers

Six adults (age range 20–27 years; mean = 21.6 years) served as participants. They all had normal or corrected-to-normal vision.

21.1.1.1 Apparatus

The stimuli were produced using an Apple Power Macintosh G4 computer (with Mac OS 9.2) and were displayed on a CRT monitor (Sony 21-inch color monitor, refresh rate 75 Hz) in a dimly lit room. The viewing distance was 57 cm, and a chin rest was employed to maintain constant viewing distance.

21.1.1.2 Stimuli

Stimuli were presented on a gray background. The moving object was a picture of a car, as shown in Fig. 21.1. The picture size was 1.2-deg wide and 0.7-deg high. A white fixation cross was presented at the center of the screen, and a white dot (0.08 deg in diameter) was presented as a flash probe. The object moved horizontally by 5 pixels per frame (corresponding to 7.5 deg/s), with the movement trajectory above the fixation point. The distance in the vertical dimension from the fixation point to the bottom of the car was approximately 0.2 deg. The flash was presented for one frame (approximately 13.3 ms) 1.4 deg above the fixation point. The vertical distance between the roof of the car and the position of the flash was approximately 0.5 deg. The car picture appeared 5.6 deg left or right from the fixation point, moved toward the center of the screen, and went through to the opposite side of the screen. The duration of the complete motion sequence was 1533.3 ms (115 frames). The flash and the fixation point were always aligned on the vertical axis. However, the relative horizontal position between the flash and the car picture varied from trial to trial according to lag condition.

21.1.1.3 Procedure

The observer's task was to decide whether the flash appeared to the left or right relative to the "center" of the car picture (2 AFC). Observers were strictly instructed to fixate on a fixation cross while it was presented on the screen.

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The experimental design was as follows. For factor of object motion, there were three types of motion. In the conditions in which the car picture moved (forward, backward conditions), the picture was initially presented 5.6 deg left or right of fixation. When the car picture appeared on the left side, it moved toward right, and vice versa. The car picture moved at constant speed of 7.5 deg/sec to the opposite side of fixation point. When the car picture reached 5.6 deg to the opposite side of fixation point, it disappeared. In the condition in which the car did not move (stationary condition), the picture was presented above the fixation (with spatial shift according to lag condition) for 1533.3 ms. For the factor of object orientation, there were two types of object orientation, the picture of the car facing left or facing right.

As for the factor of horizontal lag between the flash and the picture of car, we used seven different lags: −0.6, −0.4, −0.2, 0, 0.2, 0.4, 0.6 deg (−6, −4, −2, 0, 2, 4, and 6 temporal frames in the time domain). We expediently defined the horizontal midpoint of the car picture as its center. When the lag was 0 deg, the flash appeared above the fixation cross when the center of the car was just above the fixation. In other lag settings, when the lag is −0.6 deg, the flash was presented six temporal frames before the center of the car picture reached a point directly above the fixation point. Observers performed 672 trials in total: 3 (leftward motion, rightward motion, or stationary) × 2 (facing left or right) × 7 (different lag settings) × 16 (repetitions of each condition).

At the beginning of each trial, the fixation cross was presented at the center of the screen. The car picture appeared on the screen 500 msec after the fixation cross appearance. In all conditions the car picture was presented for 1533.3 ms. Observers made their response by pressing the left or right arrow key, after which the fixation cross disappeared. No feedback was given to the observers. The next trial was then presented with a 1-sec intertrial interval. A short break was given to the observers every sixty trials (approximately once every 4 min), which the observers used to take a short rest if needed. Prior to the experiment, observers completed a practice session consisting of thirty trials. The entire experiment time was about 60 min, including instruction and practice session.

21.1.2 Result and discussion

Figure 21.2 shows the averaged FLE in each condition for six observers in the FLE experiment. The data were collapsed across motion direction because there was no difference between leftward and rightward motion, and recombined into forward (leftward-facing left trials and rightward-facing right trials) or backward motion (leftward-facing right trials and rightward-facing left trials). Thus, in this experiment, the *actual amount* of flash lag was defined as the difference between the stationary condition (which was used to estimate each observer's "subjective" center of the car picture) and the forward motion condition, or between the stationary condition and the backward motion condition. For each observer, we derived a psychometric function and calculated the 50% probability of judging "left" or "right" for each of the conditions. We observed significant differences between conditions ($F(2, 10) = 14.5$, MSE $= 20.7$, $p < .01$). The FLE was significantly smaller for stationary

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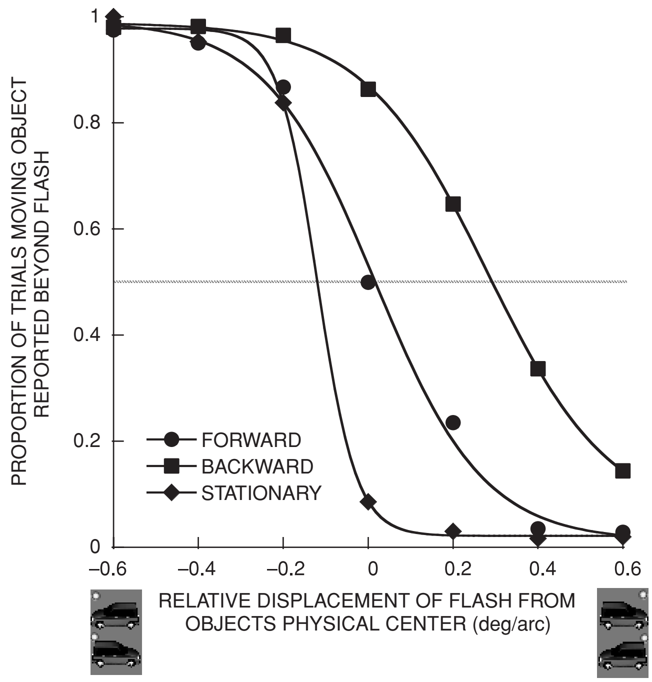

Fig. 21.2 Result of flash-lag experiment.

condition than for the other two conditions ($p < .01$ for both forward and backward conditions), which indicates that FLE occurred in this display. Then, we took the difference in the probability judgment between the forward motion condition and the stationary condition as representing the actual amount of FLE in forward motion, and the difference in the probability judgment between the backward motion condition and the stationary motion condition as representing the actual amount of FLE in backward motion. A separate statistical analysis revealed that the difference in FLE between forward motion condition and backward motion condition was significant [$t(5) = 5.5$, $p < .01$]. A larger FLE occurred for backward motion condition than for forward motion condition.

This result, that backward motion produced larger FLE than forward motion, was surprising, because it was opposite to the findings in RM (Freyd & Miller 1992; Reed & Vinson 1996; Vinson & Reed 2002). We replicated this result with a different stimulus (a picture of fish shown in Fig. 21.3), and thus the effect of forward/backward motions on FLE (i.e., the opposite effect shown in RM) seems robust. It is worth considering the quality of motion (discrete or smooth motion) in discussing knowledge-based effects. In RM, with discrete motion, the effect of typical motion was consistently found (Reed & Vinson 1996; Vinson & Reed 2002), but it was not consistently found with smooth motion (Freyd & Miller 1992; Nagai & Yagi 2001). These findings suggested that discrete motion of an object was better to show a typical motion effect in RM. However, in the present experiment, we followed a standard experimental procedure of FLE studies for better comparison of FLE with RM.

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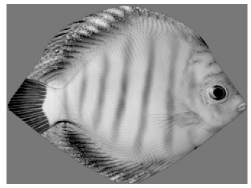

Fig. 21.3 Example of stimuli used in preliminary test.

Before we consider why the effect in FLE was opposite to that in RM, it is necessary to confirm the typical motion effect in RM with smooth motion.

21.2 Representational momentum experiment with left or right judgment

As mentioned in the introduction, previous studies of RM have shown that conceptual knowledge of objects' and animals' typical motions in the real world influenced the magnitude of RM (Freyd & Miller 1992; Reed & Vinson 1996; Vinson & Reed 2002; but see Halpern & Kelly 1993[1]; Nagai & Yagi 2001). However, the typical motion effect was not consistently observed with smooth motion: for example, Freyd and Miller (1992) showed the effect, but Nagai and Yagi (2001) did not. Here we tried to replicate the typical motion effect with smooth motion. A standard RM paradigm employs the same–different judgment between the final position of the moving stimulus and the position of the subsequently presented probe. However, in this experiment, the left or right judgment as in the FLE experiment was used to allow a more direct comparison between the typical motion effects on FLE and RM.

21.2.1 Method

21.2.1.1 Observers

Six adults (ranged 20–27 years; mean = 22.3 years) served as participants. They all had normal or corrected-to-normal vision. Three of those participants had participated in the flash-lag experiment.

21.2.1.2 Stimuli

The stimulus used for the moving (or staying) object was the same picture of a car as used in the FLE experiment. In this RM experiment, no fixation point or flash was presented because keeping eyes at the fixation point reduces the magnitude of RM (Kerzel 2000; Nagai & Saiki 2006), and elements other than a moving object bias the judged final position of

[1] In Halpern and Kelly (1993), only *forward* discrete motions of a fox, a motorcycle, a rhinoceros, a truck, and a ball were used, and they did not show consistent effect of typical speeds in the real world like a truck moves faster than a fox. In contrast, most of the studies used *forward and backward* discrete motions of real-world objects and showed different magnitude of RM for these two motions (Freyd & Miller 1992; Reed & Vinson 1996; Vinson & Reed 2002). These suggest that comparing forward and backward motions was a sensitive way to show typical motion effects and the relative difference in typical speed between objects could not affect RM. In the present study we used the sensitive method to examine the typical motion effect.

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the object to the other element (Hubbard & Ruppel 1999). The car picture appeared at the same position (5.6 deg left or right from the horizontal center of the display) and moved with the same speed (or remained still as in FLE stationary condition).

The disappearing location of the object was randomly set from trial to trial, in the range from −1.0 to +1.0 deg from the exact center of the screen. In the forward and backward motion conditions, the motion duration differed according to where the object disappeared. When the object disappeared at the center of the screen, motion duration was 746.48 ms (ranged from 613.1 ms to 879.8 ms). In the stationary condition, the car picture was presented near the center of the screen (at the center with spatial jitter ranged from −1.0 to +1.0 deg) for 746.48 ms. After the car picture disappeared, observers were shown a blank display (entirely gray) for 1 sec. After this retention interval, the car picture was shown again as a probe, with a spatial displacement according to condition. This probe picture remained on screen until participants' response.

21.2.1.3 Procedure

The observer's task was to decide whether the probe appeared to the left, or right, relative to the car picture in the final frame (two-alternative forced-choice). Observers were not informed whether they should track the moving stimulus or not, as in the standard experiment paradigm of RM.

The experimental design was similar to that of the FLE experiment except for the probe presentation. There were seven different probe positions (−0.6, −0.4, −0.2, 0, +0.2, +0.4, +0.6 deg). Positive values indicate that the probe was shifted in the direction of the picture motion from the final position of the car picture. Observers performed 672 trials in total: 3 (leftward motion, rightward motion, or stationary) × 2 (facing left or right) × 7 (probe positions) × 16 (repetitions per condition).

The beginning of each trial was indicated with a short beep sound. The car picture appeared on the screen 500 ms after the beep. Observers made their response by pressing the left or right arrow key. No feedback was given to the observers. They went on to the next trial, after 1 sec of intertrial interval. A short break was inserted every sixty trials (approximately once every 5–6 min), and observers took a rest if they needed to. Prior to the experiment, observers completed a practice session consisting of thirty trials. The entire experiment time was about 70 min including instruction and practice session.

21.2.2 Result and discussion

Figure 21.4 shows the averaged RM shift in each condition for six observers. The shift was defined as judged error relative to the final position. Collected data were collapsed across motion direction (there was no difference between leftward and rightward motion) and recombined as forward (leftward-facing left trials and rightward-facing right trials) or backward motion (leftward-facing right trials and rightward-facing left trials).

The overall results resemble those of the previous FLE experiment. The magnitude of RM was nonsignificantly larger for backward motion than for forward motion. However, we found no significant difference from the zero baseline for any conditions, which indicates

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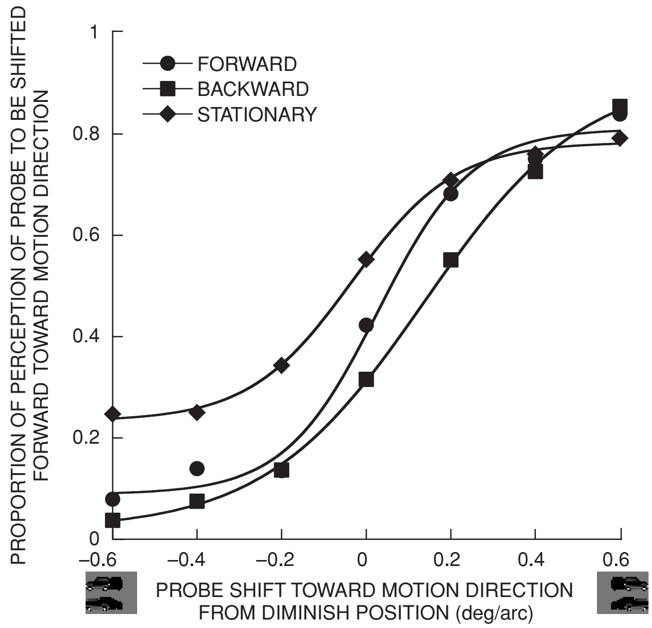

Fig. 21.4 Result for RM experiment, when judging whether the probe was shifted left or right from final frame.

that no significant RM shift occurred in this experiment. This might be due to the task we used. In this experiment, to make a direct comparison between the FLE and RM experiments, we asked observers to decide whether the probe shifted left or right. In the next experiment, we used a same/different judgment paradigm, which is the method more widely used in RM studies (e.g., Freyd & Finke 1984).

21.3 Representational momentum experiment with same/different judgment

In the previous RM experiment with the left/right judgment, the results showed no RM effects. In this experiment, each observer performed the same/different judgment on the position of the probe, but the other stimuli settings and procedures were kept identical to those in the previous experiment. This procedure was expected to increase the RM effect and to show the typical motion effect.

21.3.1 Method

21.3.1.1 Observers

Nine adults (ranged 19–31 years; mean = 22.2 years) served as participants. None had participated in the previous two experiments. They all had normal or corrected-to-normal vision.

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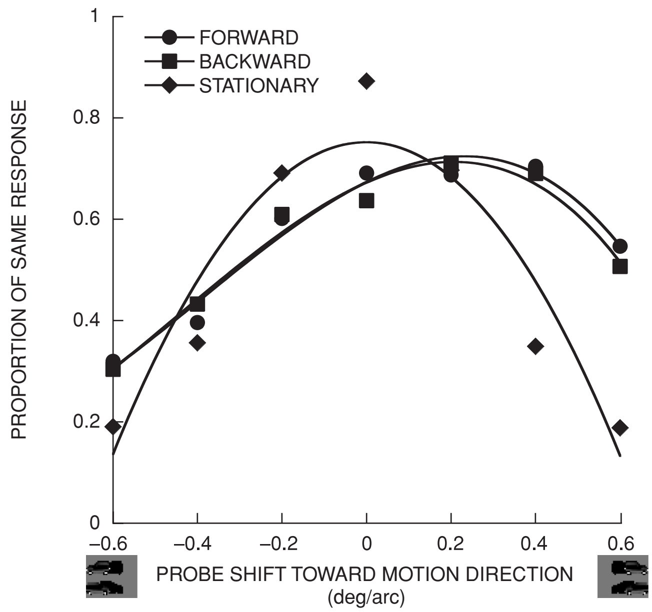

Fig. 21.5 Same response proportion and quadratic fit.

21.3.2 Result and discussion

Figure 21.5 shows the averaged proportion of the same response in each condition for nine observers in this second RM experiment with the same/different judgment. For each observer's data, we calculated a weighted mean for each condition. Figure 21.6 shows the average weighted mean and standard error for each condition. Statistical analyses revealed that the weighted mean in the forward condition was significantly larger than zero ($t(8) = 1.9$, $p < .05$) but was not in the backward or stationary conditions.

With the same/different judgment, we observed significant RM and the expected effect of forward versus backward motions. This suggests that the typical motion effect shown in previous discrete-motion RM studies (Freyd & Miller 1992; Reed & Vinson 1996; Vinson & Reed 2002) can also be observed with smooth motion, although the magnitude of it was small (but see Nagai & Yagi 2001).

21.4 General discussion

These studies aimed to directly compare the typical motion effects in FLE and RM. The first experiment showed that FLE was larger for car's backward motion than for its forward motion; thus FLE shows a reversed-typical motion effect. This was the robust effect because it was replicated also with motion of a biological object (e.g., a fish). Although it was the opposite to the typical motion effect found previously for RM, this study consistently showed the influence of higher cognitive knowledge about objects' typical motions on

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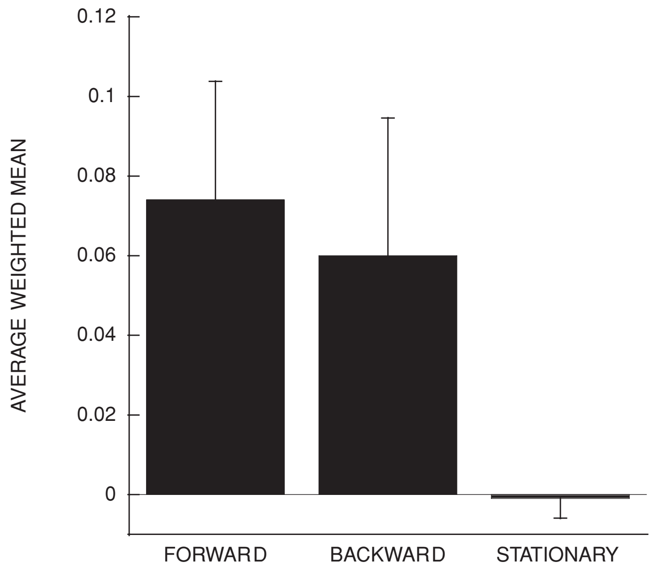

Fig. 21.6 Averaged weighted mean for each condition.

FLE. The second experiment did not show any RM for the left/right judgment task. The third experiment used the same/different judgment and replicated RM and typical motion effects that had been consistently observed before with discrete stimulus presentation (Reed & Vinson 1996; Vinson & Reed 2002). Although we used different tasks in FLE and RM, we presented the same motion stimuli in both FLE and RM experiments. Thus, the present study provides the first basis for comparing and discussing the effect of cognitive knowledge on the two motion-based spatial errors.

Here we attempt to explain the discrepant results between FLE and RM with two different typical motion effects: a "perceived speed" while a moving object is *actually* presented versus an "internal model speed signal" after the object has disappeared. In the real world, cars move forward most of time when they move, and their backward motions are much less frequent. Thus, humans could have an internal model for each type of object's typical motions: for example, a car mostly moves forward and only sometimes backward. In the case of car motion, the subjective speed estimate from the internal model would be larger for forward motion and smaller for backward motion. However, because objects in both forward and backward conditions move with the same actual speed on the CRT display, the difference between incoming sensory input and the output of the internal model would be smaller for forward motion and larger for backward motion. If perceptual speed is modified by the magnitude of such a difference (or subjective prediction error), then the perceived speed of backward motion would be larger than forward motion, and thus FLE would be larger for backward motion.

In the RM experiment paradigm, however, this perceived speed modulation by subjective prediction error could not occur, and only the internal model speed could influence the

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magnitude of RM. The critical difference between FLE and RM stimulus presentations was whether the car's motion was still presented at the time of the "judgment marker." In the FLE experiment, the car motion was still presented at the time of the flash, and observers could access and use this sensory input signal to make their judgment. Thus, the perceived speed modulation (based on the subjective prediction error) influenced the magnitude of FLE. However, in the RM paradigm, no moving car was presented at the time of probe presentation, which meant there was no sensory input signal of motion at the time of judgment. Thus, the perceived speed modulation did not occur in the RM paradigm, and we did not get the result that a car's backward motion produced larger RM than its forward motion. Instead, we suggest that the "internal model" on objects' typical motions influenced RM. After the moving car disappeared, observers could not use the sensory input of the motion signal but used only the output speed signal of the internal model of the object's typical motions (e.g., a car moves faster for its forward than backward motion). Therefore, larger RM for the forward motion was observed than for the backward motion. This is the typical motion effect as found in previous studies (Freyd & Miller 1992; Reed & Vinson 1996; Vinson & Reed 2002).

This internal model of an object's typical motions could also work during the blank screen intervals during discrete motion presentation. For example, in Vinson and Reed (2002) the picture of the object was displayed for 250 ms and followed by a 250 ms blank interstimulus interval (ISI). The motion sequence consisted of four frames of object presentations interleaved with ISIs. In this discrete motion case, the internal model's influence could be applied during each ISI, which would reduce the greater perceived speed for backward motion, and which would increase the lower perceived speed for forward motion, to yield the typical motion effect (i.e., the forward motion of a car, fish producing larger RM than their backward motion).

In contrast, this study, Nagai and Yagi (2001) and Freyd and Miller (1992) used smooth motion of the object (i.e., no ISI), thus some of them yielding the small typical motion effect (this study) or no such effect (Nagai & Yagi 2001) in RM. In the case of smooth motion, the typical motion influence by the internal model could not occur during its motion presentation because there were no blank ISIs. Thus, this internal model influence might be overcome by the perceived speed modulation based on the difference between sensory input and internal model output because these two influences worked in opposite directions to each other.

In sum, the present study found that knowledge of typical motions of objects influenced both FLE and RM, although such knowledge differently affected them. This is the first report that cognitive factors influence FLE. Many other factors can be examined and compared in both FLE and RM: eye movements (in FLE, Nijhawan 2001; in RM, Kerzel 2000; Nagai & Saiki 2006), human internal models of physical laws (only investigated so far in RM: gravity, implied friction, see Hubbard 1995b for review). We suggest that comparing the influence of various cognitive factors on FLE and RM will lead to a better understanding of spatial errors and motion perception mechanisms.

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