Representational momentum modulated by object spin

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ORIGINAL ARTICLE

Representational momentum modulated by object spin

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Abstract

The present study examined whether the spin of a horizontally translating target in an animation movie modulates the magnitude of forward displacement of a remembered final position of the target. The rotation of an axis bar corresponding to the diameter of a circular target represented the target's spin. There were three spin conditions: forward, backward, and without spin. The observers had to manually localize the vanished position of the target without eye movements. Experiment 1 showed that forward displacement was larger in the forward spin condition than in the backward spin condition and also confirmed that this modulation of forward displacement by object spin was not due to observers' eye movements. Experiment 2 demonstrated that the modulation of forward displacement was not observed when horizontal translational motion was removed from the stimuli, suggesting that the interaction between the target's spin and the horizontal translational motion is critical. These results indicate that implicit friction due to object spin modulates forward displacement without the involvement of eye movements.

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Introduction

The vanished position of a moving object is often mislocalized in the direction of the object's motion. This is called *forward displacement* of the object. Previous studies have reasoned that forward displacement occurs because the movement of objects cannot stop instantaneously in our mental representation (*representational momentum*: Freyd & Finke, 1984; Hubbard, 1995b). Representational momentum is considered a type of naive theory of physical principles, implemented in our cognitive system (internalized naive physics: McCloskey & Kohl, 1983). Previous studies have reported several kinds of internalized naive physics that influence the magnitude of forward displacement: implied velocity (Finke, Freyd, & Shyi, 1986; Freyd & Finke, 1985), gravitation (Hubbard, 1990), and friction (Hubbard, 1995a).

On the other hand, not only cognitive factors (i.e., the observer's knowledge or belief about physical laws) but also an oculomotor factor appears to determine forward displacement. Kerzel (2000) showed that forward displacement occurred only when the observers' pursuit eye movements overshot the actual vanished position of a smoothly moving target. These results indicate that the forward shift of visible persistence of the target, caused by the overshooting of pursuit eye movements after the target's disappearance, was a source of forward displacement.

The effect of representational friction has also been explained by the oculomotor factor (Kerzel, 2002). A previous study used a moving target sliding along the surface of a ground-like square, and obtained a significant reduction of forward displacement as evidence of implied friction (Hubbard, 1995a). However, after placing an additive fixation cross at the corner of the surface stimulus, Kerzel failed to obtain the reduction in forward displacement by adding the friction surface. From these results, Kerzel concluded that the surface contacting the target acted as a brake on observers' eye movements rather than on the mental representation of the target. That is, a decrease in the velocity of smooth pursuit eye movements on a structured background (Collewijn & Tamminga, 1984) may reduce the oculomotor overshoot, leading to the reduction in forward displacement.

Although it is plausible to explain the effect of friction in that an oculomotor factor plays a critical role (Kerzel, 2002), it does not necessarily mean that the implied friction does not affect forward displacement. It has been shown that a moving target slightly separated from the friction surface produced larger forward displacement than a target that contacted the friction surface (Hubbard, 1995a). We surmise that the difference in eye movements between the separated and contacted conditions is not a good explanation for the difference in the magnitude of forward displacement because the small separation between the target and surface would not be sufficient to affect the velocity of pursuit eye movements. Instead, these results are consistent with an explanation related to implied friction. Therefore, we suggest that both oculomotor factors and internalized naive physics concurrently contribute to forward displacement (Hubbard, 2005, 2006; Kerzel, 2006).

The present study aimed to provide evidence for the premise that implied friction represented by an object's spin modulates the magnitude of forward displacement, excluding the involvement of eye movements. Although previous studies tested the effect of implied friction on forward displacement (Hubbard, 1995a; Kerzel, 2002), the specific purpose of this study was to extend the finding to another type of stimuli. In accordance with this aim, we employed a spinning object as a target because implied friction was expected to be changed, depending on the direction of the object's spin. For example, when a ball translates rightward on the surface in the real world, the spin motion occurs in the clockwise direction. On the other hand, when a spin in the counterclockwise direction of motion is artificially given to the ball translating rightward, the physical strength of the translation is strongly reduced due to the frictional resistance between the ball and surface. We expected that the observers would implicitly estimate the impetus of the target, depending on the relative motion direction between the target's spin and translation. Consequently, the forward displacement of the target would be influenced by the spin.

The goal of the present study was to demonstrate the effect of implied friction by object spin on forward displacement without any involvements of eye movements. In Experiment 1A, we tested the effect of the spin direction of the target on forward displacement under the condition where observers' eye movements were restricted. In Experiment 1B, we monitored observers' eye movements during the experiment to check the contribution of eye movements to the spin effect. In Experiment 2, we examined whether the spin direction per se or the interaction between spin and translating direction was critical for displacement.

Experiment 1A

In Experiment 1A, we tested the effect of spin direction on the forward displacement of a translating object. Based on the idea of implied friction (Hubbard, 1995a), we hypothesized that the forward displacement of a target with a forward spin would be larger than that of a target with a backward spin because the former would produce smaller implied friction between the target and surface than would the latter.

Method

Observers Eighteen graduate and undergraduate students from Kyushu University voluntarily participated in this experiment. All the participants had normal or corrected-to-normal visual acuity and were naive as to the purpose of the study.

Apparatus and stimuli The stimuli were displayed on a CRT monitor (EIZO FlexScan T761, Japan) with a 1024 × 768 pixel resolution and a 75-Hz vertical refresh rate. A PC/AT compatible computer was used to control the presentation of the stimuli and collection of data. Figure 1 provides a schematic representation of the stimuli used in the experiment. The background of each stimulus was split into two gray areas, differentiated by luminance; the lower area (87.6 cd/m^2) was brighter than the upper area (18.9 cd/m^2). With a viewing distance of 60 cm, the upper area was shorter than the lower area by a visual angle of 1.0°. A border between different gray luminance areas was defined as the "surface" of the lower "ground" area. A red fixation cross was presented at the center of the screen (CIE *xy* coordinates: .54/.34, 20.0 cd/m^2). The target was a gray circle (87.6 cd/m^2), subtending 1.0° in diameter and smoothly translating on the surface, which was 0.6º above the center of the fixation cross. The speed of translation of the target was 9.42 deg/s. The target had a black bar running along its axis (18.9 cd/m^2). In the forward spin condition, the axis was smoothly rotated in a clockwise direction when the motion direction was rightward and in a counterclockwise direction when the motion direction was leftward. In the backward spin condition, the relationship between rotation and motion direction was reversed. The speed of rotation was set at three revolutions per second in both conditions, to represent the rigid motion of a circle with spin. In the without spin condition, the axis bar remained fixed with a random orientation during the presentation of the motion sequence. In all the conditions, the initial orientation of the axis bar was randomized on each given trial.

Procedure and design The experiment was conducted in a darkroom. The observers initiated each trial by pressing the spacebar of a computer keyboard. After a delay of 500 ms, an animation sequence was initiated, wherein a target circle smoothly moved leftward or rightward immediately after the onset of the target. In any given trial, the initial position of the target ranged from a distance of 3.3° to 5.3° from the midpoint of the display, and once the target appeared, it moved toward the midpoint of the display. After the target vanished, the observers were required to report the memorized center of the target by moving a black cross cursor (87.6 cd/m^2) across the screen and clicking the left mouse button at the desired point. In a given trial, the appearance position of the cursor was randomly determined within an imaginary square centered on the vanished position with edges of 4.3°. The observers were requested to maintain their gaze on the fixation cross throughout the trial. Each

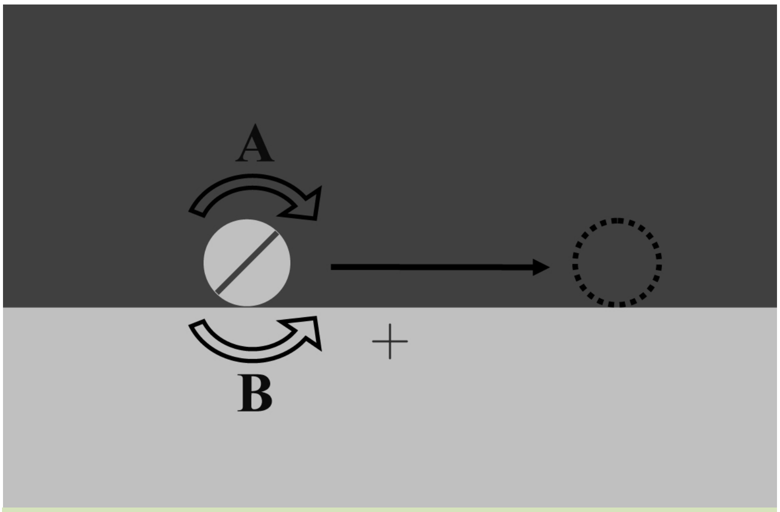

Figure 1: Schematic representation of stimuli used in Experiments 1A and 1B. This figure illustrates a magnified view of the central portion of the display. The target circle moved leftward or rightward in the horizontal direction, in conjunction with the clockwise or counterclockwise rotation of the axis bar. The rotation of the axis bar indicated the smooth spin and rigid motion of the circular target. In this figure, the curved arrow A indicates a forward spin, while the curved arrow B indicates a backward spin. The straight arrow indicates the direction of the target's translational motion. The circle drawn with dotted lines represents the vanished location of a target. The fixation cross printed in gray was actually red (see the text).

observer performed 120 experimental trials involving two within-subject factors: spin direction (forward, backward, and without spin) and traveling distance (2.11°, 3.17°, 4.22°, 5.28°, and 6.34°). Each combination of spin direction and traveling distance was repeated eight times.

Results

In this and subsequent experiments, analyses of target localization were based on displacement in a horizontal axis because we were interested in the magnitude of forward displacement of a horizontally moving target. In this experiment we employed the value of horizontal displacement in the direction of target motion as an index of forward displacement. A two-way repeated measure analysis of variance (ANOVA) on forward displacement with spin direction and travelling distance as factors demonstrated significant main effects of both spin direction, $F(2, 34) = 3.98$, $p < .05$, and travelling distance, $F(4, 68) = 20.50$, $p < .001$. However, there was no interaction between the two factors, $F(8, 136) = 1.17$, $p > .32$. Based on the main effect of spin direction, post hoc comparisons, using Ryan's method (Ryan, 1959, 1960) indicated that a target with a forward spin produced significantly greater forward displacement than did a target with a backward spin, $t(34) = 2.65$, $p < .05$. However, forward displacement in the without spin condition did not differ from that in the forward spin, $t(34) = .49$, $p > .62$, and backward spin conditions, $t(34) = 2.16$, $p > .03$ (the nominal significance level was .03).

To assess the significance of forward displacement, we employed a confidence interval of the mean in each spin condition. The 95% confidence intervals (0.28°±0.17° for the forward spin condition; 0.23°±0.18° for the backward spin condition; 0.24°±0.17° for the without spin condition) did not overlap with 0, which means actual position of the target, guaranteeing significant forward displacement in all spin conditions.

We calculated relative forward displacement by subtracting the magnitude of forward displacement in the without spin condition from that in the forward spin and backward spin conditions (Figure 2). A two-way ANOVA on relative forward displacement with spin direction and travelling distance as factors demonstrated a significant main effect of spin direction, $F(1, 17) = 5.44$, $p < .04$. However, a main effect of travelling distance, $F(4, 68) = 1.01$, $p > .40$, and the interaction between the two factors, $F(4, 68) = 1.32$, $p > .27$, were not significant.

Discussion

Consistent with previous studies on representational momentum (e.g., Freyd & Finke, 1984; Hubbard, 1995b), Experiment 1A demonstrated significant forward displacement in all spin conditions. More importantly, a significant effect of spin direction on forward displacement was obtained, that is, forward displacement in the forward spin condition was significantly larger than that in the backward spin condition. The results are consistent with the idea that implied friction, a type of internalized naive physics, altered the magnitude of forward displacement (Hubbard, 1995a, 1995b).

Was it possible that the observers' involuntary eye movements while viewing the stimulus movie somehow contributed to the modulation of forward displacement? The possibility of the involvement of eye movements is worth mentioning because forward displacement of the end point of a smoothly moving target, measured by a manual localization task, has been explained as a byproduct of an overshoot of smooth pursuit eye movements (e.g., Kerzel, 2000, 2005, 2006). The oculomotor system controls the velocity of smooth pursuit in order to minimize retinal slip (e.g., Morris & Lisberger, 1987; Shibata, Tabata, Schaal, & Kawato, 2005). However, the direction of an object's spin can hardly be expected to affect the minimization of retinal slip. Moreover, even if saccadic eye movements toward the target possibly occurred and it overshot the vanished point of the target, there is no convincing reason why the landing point of the saccadic eye movements was systematically biased depending on the spin direction. Although the reasons stated above seem valid, theoretical conclusion that any oculomotor factors are not related to the significant spin effect should be empirically supported; it seemed necessary to actually monitor observers' eye movements during the experiment. Experiment 1B was performed to confirm potential roles of observers' eye movements on the spin effect.

Experiment 1B

This was a follow-up experiment to check whether oculomotor factors were related to the spin effect. Previous studies suggested that eye movements in the direction of target motion can play a critical role for forward displacement (e.g., Kerzel, 2005). If eye movements contributed to the spin effect found in Experiment 1A, any differences of observers' eye position between forward and backward spin conditions would be observed.

Method

Observers Three naive individuals were newly recruited. They had normal or corrected-to-normal visual acuity.

Apparatus, stimuli, procedure, and design This experiment was identical to those in Experiment 1A, except that observers' eye movements were monitored with an eye-mark recorder (EMR-NL8B, NAC Image Technology, Japan), and eye positions were recorded at 60 Hz during the experiment.

Results

Target localization A two-way ANOVA on forward displacement with spin direction and travelling distance as factors demonstrated significant main effects of both spin direction, $F(2, 4) = 20.68$, $p < .008$, and travelling distance, $F(4, 8) = 21.93$, $p < .002$. However, there was no interaction between the two factors, $F(8, 16) = .85$, $p > .57$. Post hoc comparisons, using Ryan's method indicated that a target with a forward spin produced significantly greater forward displacement than did a target with a backward spin, $t(4) = 6.27$, $p < .004$, and without spin conditions, $t(4) = 4.37$, $p < .02$. However, forward displacement in the backward spin condition did not significantly differ from that in the without spin condition, $t(4) = 1.90$, $p > .13$.

Relative forward displacement was calculated as in Experiment 1A (Figure 3A). A two-way

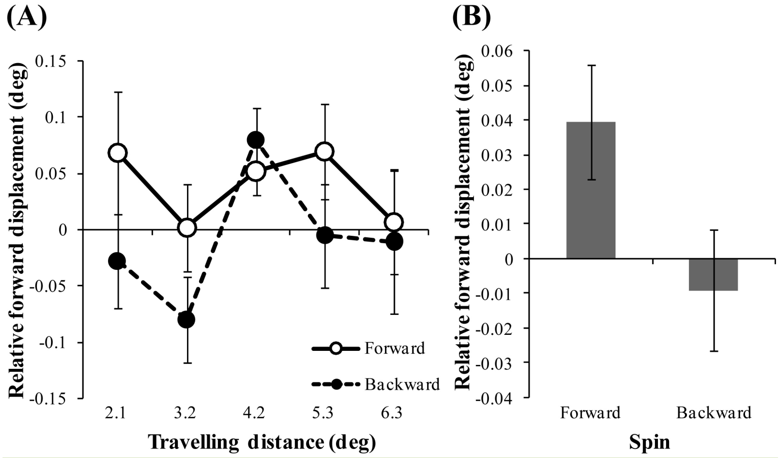

Figure 2: Results of Experiment 1A.
(A) Mean relative forward displacement as a function of travelling distance. (B) Mean relative forward displacement in the forward spin and backward spin conditions compared with that in the without spin condition. Larger values indicate larger forward displacement. Error bars indicate standard errors of means.

ANOVA on relative forward displacement with spin direction and travelling distance as factors demonstrated a significant main effect of spin direction, $F(1, 2) = 370.03$, $p < .003$. However, a main effect of travelling distance, $F(4, 8) = .60$, $p > .67$, and the interaction between the two factors, $F(4, 8) = 1.47$, $p > .29$, were not significant.

Eye movements The horizontal component of eye positions was subject to the analysis. We ignored the variation of eye positions in the vertical dimension since motion direction of stimuli was horizontal and hence only the variation of eye positions in the horizontal dimension seemed to be informative to discuss potential relationship between forward displacement along motion direction and eye positions of observers. A two-way ANOVA on average eye position with spin direction and travelling distance as factors was performed. However, a main effect of spin direction, $F(2, 4) = .32$, $p > .74$, that of travelling distance, $F(4, 8) = 2.24$, $p > .15$, and the interaction between the two factors, $F(8, 16) = .66$, $p > .72$, were not significant.

Relative eye position was derived from subtracting average eye positions in the without spin condition from those in the forward spin and backward spin conditions for each observer (Figure 3B). A two-way ANOVA on relative eye position with spin direction and travelling distance as factors was performed. However, a main effect of spin direction, $F(1, 2) = .06$, $p > .83$, that of travelling distance, $F(4, 8) = .49$, $p > .74$, and the interaction between the two factors, $F(4, 8) = .76$, $p > .58$, were not significant.

Target localization × Eye movements To

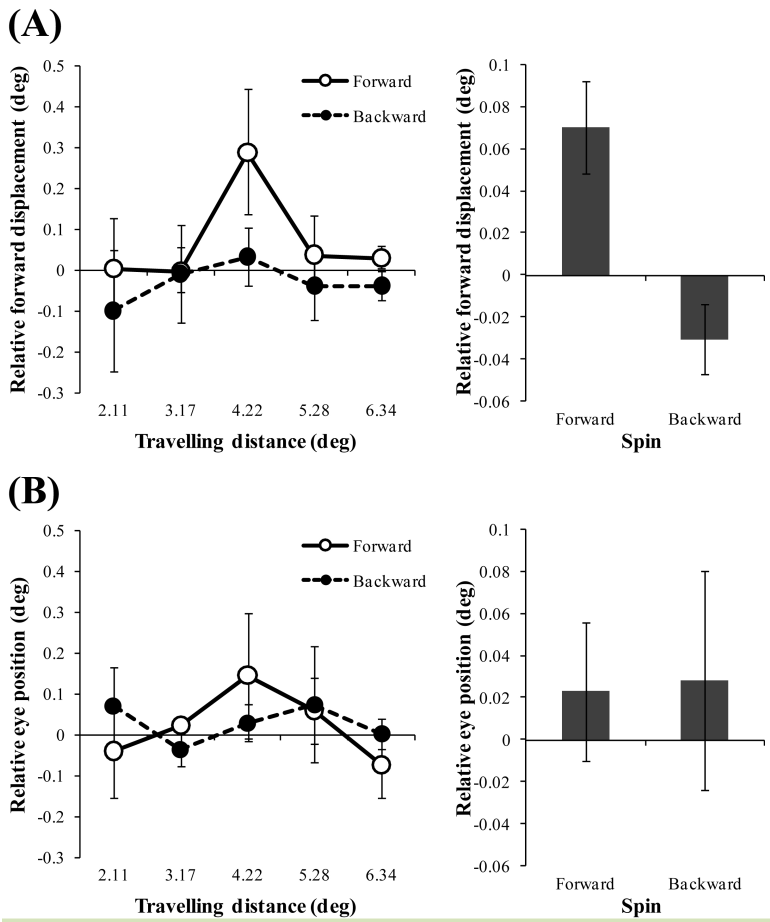

Figure 3: Results of Experiment 1B.
(A) Left: Mean relative forward displacement as a function of travelling distance. Right: Mean relative forward displacement in the forward spin and backward spin conditions compared with that in the without spin condition. Larger values indicate larger forward displacement. Error bars indicate standard errors of means. (B) Left: Mean relative eye position as a function of travelling distance. Right: Mean relative eye position in the forward spin and backward spin conditions compared with that in the without spin condition. Larger values indicate larger fixation bias in the direction of target motion. Error bars indicate standard errors of means.

confirm the interaction between target localization and eye movements, we performed planned comparisons between forward and backward spin conditions on each travelling distance. On relative forward displacement, although significance was marginal, the spin effect was found in 4.22 deg condition, $t(2) = 3.07$, $p < .10$; the effect size was large, $d = .90$. On relative eye position, however, there was no significant spin effect in each travelling distance condition, $ts(2) > 1.61$, $ps > .24$. Furthermore, relative forward displacement and relative eye position in each travelling distance averaged across observers were not significantly correlated, $r^2 = .21, p > .18$.

Discussion

In this experiment, we replicated the results of Experiment 1A: forward displacement in the forward spin condition was significantly larger than that in other conditions. On the other hand, it was confirmed that variation of eye positions in the horizontal dimension during stimulus presentation was not the cause of spin effects on forward displacement. Therefore, we conclude that observers' eye movements do not explain the spin effect we obtained in Experiments 1A and 1B.

Besides, the analysis of forward displacement in Experiments 1A and 1B revealed the significant main effect of travelling distance. In any spin condition, the longer the target moved, the smaller the forward displacement was. The cause of the effect of travelling distance seems to be related to foveal bias. There is a tendency to erroneously localize a visual target toward the fovea when the target is presented in the periphery (Müsseler, van der Heijden, Mahmud, Deubel, & Ertsey, 1999; Sheth & Shimojo, 2001; Uddin, Kawabe, & Nakamizo, 2005a, 2005b). Moreover, the absence of eye movements cannot eliminate this tendency (O'Regan, 1984). Additionally, the magnitude of the foveal bias increases with the increase of the eccentricity of the target (Müsseler et al., 1999). The effect of travelling distance observed in Experiments 1A and 1B can be explained as follows. The horizontal distance between the vanished position of the target and the fixation cross was about 2.2° in both the 2.11° and 6.34° conditions (and was about 1.0° in the 3.17° and 5.28° conditions). Therefore, the foveal bias would occur equally in the case of these pairs. However, because the motion direction was always centripetal when the sequence started, the foveal bias and forward displacement were added in the 2.11° (3.17°) condition but counterbalanced in the 6.34° (5.28°) condition. In this way, the interaction between the foveal bias and forward displacement might have produced the apparent effect of travelling distance. On the other hand, the analyses of relative forward displacement showed neither the main effect of travelling distance nor the interaction between spin direction and travelling distance both in Experiments 1A and 1B. These results suggest that the spin effect does not depend on travelling distance.

We interpreted the spin effect observed in Experiments 1A and 1B in terms of the interaction between spin direction and translating motion. The combination of spin and translating motion may determine the strength of implicit friction, leading to a different magnitude of forward displacement. If this combination is critical for the spin effect, it is expected that the elimination of translational motion from stimuli will result in no bias of displacement, depending on the spin direction.

Experiment 2

In order to examine the necessity of translating motion for the different magnitude of forward displacement between forward and backward spin conditions, we tested whether spin alone affected target localization. If spin direction were sufficient to modulate forward displacement, the rightward and leftward displacements would occur when the direction of spin was clockwise and counterclockwise, respectively.

Method

Observers Participants consisted of twenty observers: one of the authors (YY), eighteen naive individuals, and one participant who had previously participated in Experiment 1A. All had normal or corrected-to-normal visual acuity.

Apparatus, stimuli, procedure, and design This experiment was identical to those in Experiment 1A, except in this experiment the target did not move; it was merely spun (the axis bar was rotated). The onset position of the target was identical to the initial position of the target in Experiment 1A. Each observer performed 120 experimental trials consisting of two within-subject factors: three spin conditions (clockwise, counterclockwise, and without spin) and five presented durations (213, 319, 426, 532, and 638 ms; each duration was identical to that of the target in Experiment 1A). Each combination of spin condition and presented duration was repeated eight times.

Results

A two-way ANOVA on displacement with spin direction and presented duration as factors was performed. However, a main effect of spin direction, $F(2, 38) = 1.50$, $p > .23$, that of presented duration, $F(4, 76) = 2.24$, $p > .07$, and the interaction between the two factors, $F(8, 152) = 1.27$, $p > .26$, were not significant.

As in Experiment 1A, we employed a confidence interval of the mean in each spin condition to assess the significance of localization error. The 95% confidence interval in the counterclockwise spin condition did not overlap with 0 (0.05°±0.04°) but that in other conditions (0.03°±0.05° for the clockwise spin condition; 0.04°±0.05° for the without spin condition) did.

We calculated relative displacement by subtracting the magnitude of displacement in the without spin condition from that in the clockwise spin and counterclockwise spin conditions. A two-way ANOVA on relative displacement with spin direction and presented duration as factors was performed (Figure 4). However, a main effect of spin direction, $F(1, 19) = 1.66$, $p > .22$, that of presented duration, $F(4, 76) = 1.30$, $p > .28$, and the interaction between the two factors, $F(4, 76) = 1.24$, $p > .31$, were not significant.

Discussion

Unlike Experiments 1A and 1B, this experiment failed to show the effect of spin direction on displacement. The results suggest that a difference in spin direction is not sufficient to produce any displacement of the target. Therefore, we suggest that the interaction between spin direction and translating motion is critical for the modulation of forward displacement.

Although minute in comparison to the results of Experiment 1A, a rightward localization error significantly occurred in the counterclockwise spin condition. This rightward bias is occasionally observed in representational momentum studies (Halpern & Kelly, 1993; Kerzel, 2003). The origin of this effect is so far unknown, but it is obvious that the bias is not related to the spin effect we are interested in.

General Discussion

The aim of this study was to demonstrate the effect of a target's spin on forward displacement without eye movement. In particular, we examined whether a target's spin modulating the implied friction between a translating object and

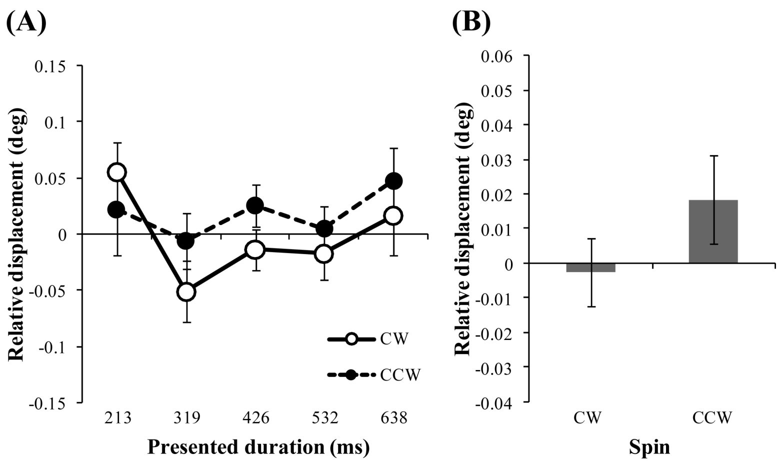

Figure 4: Results of Experiment 2.
(A) Mean relative displacement as a function of presented duration. (B) Mean relative displacement in the clockwise (CW) spin and counterclockwise (CCW) spin conditions compared with that in the without spin condition. Larger values indicate larger rightward displacement. Error bars indicate standard errors of means.

the surface altered forward displacement. As a result, we found that forward displacement was larger in the forward spin condition than in the backward spin condition when observers' eyes were fixated (Experiment 1A). Moreover, the possibility that observers' eye movements somehow affected the spin effect was excluded (Experiment 1B). Additionally, we confirmed that spin direction per se did not contribute to displacement (Experiment 2).

The results indicate that internalized naive physics affects forward displacement. In the course of human evolution (Hubbard, 1995b) or development (Perry, Smith, & Hockema, 2008), the combination between spin and translating directions of an object is internalized as a cognitive representation of the moving object. In particular, note that a translating spherical object generally has a forward spin. A translating object with a backward spin is thus inconsistent with the internalized representation of the translating spherical object, and hence the cognitive system may not consider the translating object with the backward spin as the translating spherical object. Moreover, in order for the spherical object to translate with forward spin, the friction between the object and the ground should be low. Of course, for example, the object translation on ice should not contain any spin motion, but it is unlikely for the cognitive mechanism to internalize this situation. If the relationship among translating direction, spin direction, and friction is concurrently internalized, translating motion with the forward spin should reduce the impression of friction while the translational motion with backward spin or without spin does not. Consequently, larger forward displacement is expected in the forward compared with the backward and without spin conditions, consistent with the previous study showing that the less implicit friction, the more forward displacement of the translating object (Hubbard, 1995a).

One can argue that the apparent speed provided by the interaction between the direction of spin and translation influences forward displacement. It has been suggested that the physical velocity of motion is one of the decisive factors in altering the magnitude of forward displacement (e.g., Finke et al., 1986; Freyd & Finke, 1985; Hubbard & Bharucha, 1988). In Experiments 1A and 1B, the moving target with a forward spin was possibly seen as faster than that with a backward spin, even though the actual speed of both the targets was equal. In fact, some observers in Experiment 1A verbally reported that the target stimuli with the forward spin appeared to move faster than those with the backward spin. Although the illusory speed of the target depending on a background motion did not affect forward displacement (Nagai & Saiki, 2005), the knowledge pertaining to the typical speed of a depicted object influenced displacement (Nagai & Yagi, 2001). Future research should clarify the possible impact of the apparent speed of objects on forward displacement and other phenomena related to dynamic mental representation.

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