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Abstract

When a visual object is briefly flashed, it appears to lag behind another moving object (flash-lag effect; FLE). Previous studies show that a sudden change to the moving object at the time of the flash presentation can eliminate the FLE. We examined whether the FLE is eliminated when a moving object alternates in color as it moves. Observers viewed a moving disc, the color of which did not change at all, changed only once when another object flashed, or alternated between two colors as it moved before the flash presentation. The results showed that although the magnitude of the FLE was reduced compared with the no-change condition, the FLE observed with the moving object that changed color during motion was significantly stronger than the FLE in the one-change condition. The results are discussed in relation to the object updating account of the FLE.

Keywords: Flash-lag effect; Motion continuity; Object updating

Introduction

Humans depend heavily on the perceptual system to collect information about the surrounding environment, but the perceptual system is sometimes prone to illusions that lead to inaccurate judgments. In the domain of object localization, one extensively studied illusion is the flash-lag effect (FLE), a perceptual phenomenon where a briefly-flashed stationary object appears to lag behind another moving object even though the two objects are physically aligned when the flash occurs (MacKay, 1958; Nijhawan, 1994). Studies on the FLE have found that this effect occurs in various conditions. For example, the FLE has been reported in objects with continuously changing features (Sheth, Nijhawan, & Shimojo, 2000), in objects moving in depth (Harris, Duke, & Kopinska, 2006; Ishii, Seekkuarachchi, Tamura, & Tang, 2004), in audition, and across modalities (Alais & Burr, 2003). In addition, the FLE was also found to depend on observers' eye movements (Nijhawan, 2001) and the perceptual organization of the moving object (Watanabe, 2004; Watanabe, Nijhawan, Khurna, & Shimojo, 2001). Putting the effect in a two-dimensional context, Watanabe and Yokoi (2006) found that the perceived position of the flash is not uniformly displaced, but appears to converge towards a single point behind the position of the moving object.

Ever since Nijhawan (1994) revitalized interest in the FLE within the psychology community, various explanations have been formulated to account for the effect, including motion extrapolation (Nijhawan, 1994, 1997), differential latency in processing for the flashed object and the moving object (Kanai, Carlson, Verstraten, & Walsh, 2009; Whitney & Murakami, 1998; Whitney, Murakami, & Cavanagh, 2000), motion integration and postdiction (Eagleman & Sejnowski, 2000), and attention (Baldo & Klein, 1995; Krekelberg & Lappe, 2000). However, this ongoing debate has not yet been settled.

Moore and Enns (2004) proposed a relatively new explanation of the FLE. They view the effect as the result of an ongoing object updating process based on the principle of object substitution (Enns & Di Lollo, 1997). They proposed that due to the ongoing updating process, positional information of the moving object acquired immediately after the flash presentation overwrites (replaces) that acquired at the time of the flash presentation, resulting in the illusory perception that the moving object overshoots the flash. In the case where the moving object stops at the time of the flash presentation, since there is no new information about the moving object after the flash presentation that can replace (update) previous information, the alignment of the two objects can be accurately perceived. In the same study, Moore and Enns (2004) further reported that when the visual features of the moving object, such as size and color, changed abruptly at the moment of the flash presentation and changed back immediately after the flash (we refer to this as the "One Change" motion stream), observers tended to perceive that the moving object appeared at two positions (one object with the changed color and aligned with the flash, and the other with the original color located in front of the flash) when asked about the perception at the moment of the flash presentation. The authors explained that the disruption of motion continuity by a large, transient change leads the visual system to interpret the scene as containing two separate objects. When the original object reappears at a new position after the flash, its position and color information is updated, while the information acquired at the moment of the flash presentation (which is interpreted as a different object) is spared from the overwriting process. However, if a scene-based reason is provided for the discontinuity, the object updating process is spared from disruption, preserving the representation of the original object, and thus, the FLE is observed (Moore, Mordkoff, & Enns, 2007).

According to the idea above, whether object motion continuity is preserved depends on whether only a single (i.e., the same) object is identified throughout the motion scene. The nature of object persistence has been widely studied based on object file theory (Kahneman, Treisman, & Gibbs, 1992). According to this theory, episodic representations (object files) keep track of the individual entities in a scene over space and time, and are updated

based on spatiotemporal information (i.e., location at different moments). Object files store the representations of persistent objects and mediate conscious perception, informing the observer about "which went where" (Mitroff, Scholl, & Wynn, 2005), and object identity information can be stored on a scale of seconds (Noles, Scholl, & Mitroff, 2005). Empirical evidence has suggested that object files encode identity information rather than semantic or precise physical information (i.e., physical features) about objects, and that object file representations are flexible (Gordon & Irwin, 1996, 2000). Although Mitroff and Alvarez (2007) showed that spatiotemporal information, but not surface features, effectively determines object persistence (as measured by standard object-specific preview benefits; Kahneman et al., 1992), Moore, Stephens, and Hein (2010) demonstrated that abrupt changes in surface features disrupt preview benefits, and an object feature alone could determine object persistence under some conditions. It is therefore still unclear what role object surface features play in the establishment and maintenance of object files.

An interesting question derived from the study of Moore and Enns (2004) is what would be observed if a stream of events consisted of an object moving in a uniform trajectory while its surface feature (e.g., color) keeps changing? This would represent a case in which spatiotemporal continuity suggests only a single object moving throughout the journey, but the information from surface features suggests that multiple units exist. In the present experiment, we investigated this question by introducing two conditions—Alternating stream (in which the color of the moving object alternates between two colors) and Random stream (in which the color of the moving object changes randomly between two colors)—in addition to the One Change and No Change conditions employed in the original study by Moore and Enns (2004). Based on previous work on object file theory, if spatiotemporal information dominates the formation and updating of episodic object files (so that the visual system identifies only one object in the stream), we would expect the FLE to occur even in the Alternating and Random stream conditions. This would also mean that the unexpected and highly salient change at the moment of flash presentation in the One Change stream is a necessary condition for breaking motion continuity (leading the visual system to identify multiple objects in the stream) which eliminates the FLE. In contrast, if object surface features play a significant role in maintaining object files, the history of color change in conjunction with motion would cause the visual system to conclude that multiple objects exist in the motion stream. In this case, the FLE might be eliminated because the process of overwriting previous information at each instant is largely disrupted by the color change.

Method

To examine the effect of object motion continuity on the magnitude of the FLE, we compared performance across three motion stream conditions (No Change, One Change,

and Alternating or Random) in two separate sessions with two different groups of observers.

Participants

Twenty-four paid volunteers recruited at The University of Tokyo participated as observers in the experiment. Twelve observers were assigned to the session with the Alternating stream condition, and twelve were assigned to the session with the Random stream condition. All were naïve as to the purpose of the study and had normal or corrected-to-normal vision. Informed consent was obtained from the observers prior to the experiment.

Stimuli and procedures

The stimuli used in the experiment were developed based on the previous study by Moore and Enns (2004; Part 2), and were programmed in MATLAB R2012b (MathWorks, USA) using the Psychophysics Toolbox extension (version 3.0.8; Brainard, 1997; Pelli, 1997). The stimuli were displayed on a CRT monitor with a refresh rate of 100 Hz (resolution = 800 × 600 pixels), controlled by a personal computer running the Windows 7 operating system. Observers viewed the stimuli at a distance of 60 cm in a dark and quiet environment.

All experimental stimuli were presented on a black background (luminance = 0.022 cd/m^2). The observer initiated each trial by pressing the space bar on the keyboard. After the space bar was pressed, a white fixation cross consisting of one horizontal line and one vertical line (length = 0.317°, width = 0.0453°) appeared at the center of the screen and remained throughout the trial until a response was made. Observers were required to fixate on the fixation cross throughout the trial. When the trial was initiated, a circular target stimulus (diameter = 0.907°) in either red or green (luminance = 0.47 cd/m^2) appeared either just above or below the central fixation cross at a distance of 4.171° and remained there for 500 ms. Then, the target stimulus started to move in clockwise or counter-clockwise direction on an imaginary circle (radius = 4.171°) around the fixation cross for a random angular distance of 105°, 195°, 285°, or 375° at an angular speed of 15°/frame. Each frame was displayed for 70 ms, and thus, the duration of the motion stream was 490 ms, 910 ms, 1330 ms, or 1750 ms. One of the following three possible motion streams was presented on each trial: (i) No Change, (ii) One Change, and (iii) Alternating or Random (depending on session assignment). In the No Change stream, the color of the target remained unchanged throughout the trial. In the One Change stream, the target color changed to the other color during the second last frame of the motion (which corresponds to the position just above, below, to the left, or to the right of fixation, and thus is always aligned with fixation), and then changed back to its original color in the last frame of the motion. In the Alternating stream, the color of the target alternated between red and green in each frame of the motion. In the Random stream, the color of the target changed randomly (either red or green) in each frame of its motion.

The flash stimulus was a white disc (diameter = 0.544°, luminance = 2.89 cd/m^2) presented at the position just above, below, to the left, or to the right of fixation (i.e., always aligned with fixation) at a distance of 2.901°. The flash was presented at either the third last, second last, or last frame of the motion for a duration of one frame. These three flash conditions resembled the "behind," "aligned," and "ahead" conditions in Moore and Enns (2004; Fig. 1a and 1b). In addition to these three flash conditions, there were also two baseline flash conditions for each stream condition. In the previous study, when the flash appeared, the target disc was presented at the second last position of the motion in the No Change condition, and was presented at the second last and last position of the motion in the One Change condition (Moore & Enns, 2004; Fig. 1c). However, in the present study, we included both of these baseline conditions in all stream conditions to reduce any possible difference or bias in the magnitude of the FLE elicited by the different baseline conditions in the No Change and One Change streams, thus allowing a better comparison across different stream conditions. Specifically, in the Baseline 1 condition, the target stimulus stream was identical to the "aligned" flash condition, except that the target disappeared along with the flash; in the Baseline 2 condition, the target stream was the same as the Baseline 1 condition, except that an additional target was also presented in the second last frame and disappeared along with the flash. This additional target was presented at the position where the target should appear in the last frame in a non-baseline condition (see the "small change" and "large change" conditions in Fig. 1c of Moore & Enns, 2004). Therefore, in the two baseline conditions, the target discs were presented up to the second last frame of the motion stream, and only the central fixation cross was displayed in the last frame.
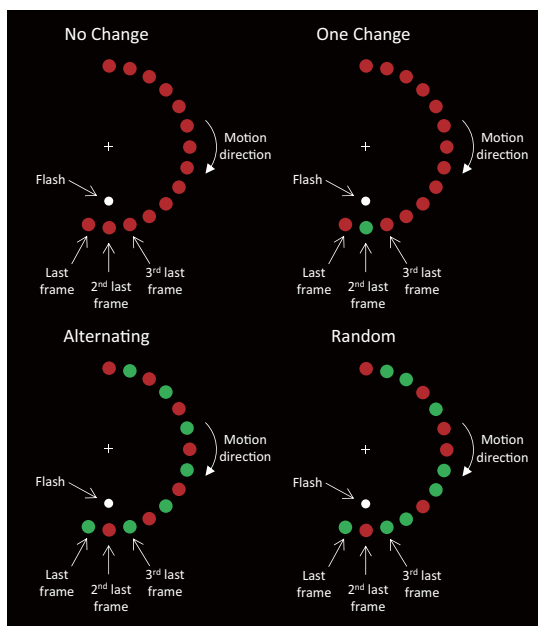

Figure 1: The four motion stream conditions employed in the present study.

Observers were required to judge, upon the disappearance of the target disc, whether the target disc was aligned with the flash (and also the fixation) at the moment when the flash occurred. They were also instructed to respond "aligned" if they saw two target discs and either one of them was aligned with the flash. There were a total of 480 trials (3 Streams conditions × 5 Flash conditions × 2 Starting Positions × 4 Travel Distances × 2 Starting Colors × 2 Motion Directions). Observers were instructed to take a five-minute break halfway through the experiment. The experimental session took about 35 minutes to complete.

Results

Following Moore and Enns (2004), we plotted the average proportion of trials where the observers reported that the target disc and the flash were aligned for each stream condition. The data are plotted separately for the sessions with Alternating and Random streams (Figure 2; only data for the two baseline flash conditions and the flash condition where the target disc and the flash were physically aligned are shown).

Separate omnibus repeated measures ANOVAs were conducted on the data in the Alternating and Random sessions of the experiment. In the Alternating session, the main effect of Flash condition [$F(2,22) = 25.777$, $p < .001$], the main effect of Stream condition [$F(2,22) = 33.997$, $p < .001$], and the Flash × Stream interaction [$F(4,44) = 9.685$, $p < .001$] were all statistically significant. The main effect of Travel Distance was not significant [$F(3,33) = 2.630$, $p = .066$]. Specific comparisons revealed that when the target disc and the flash were physically aligned (i.e., Aligned in Figure 2), there was a significantly lower proportion of "aligned" responses [i.e., P("aligned")] in the No Change condition compared to the Alternating condition, while there was a significantly higher proportion of "aligned" responses in the One Change condition compared to the Alternating condition (both at $p < .01$, adjusted for multiple comparisons). No significant difference in proportion was found between the three stream conditions in the Baseline 1 condition; a significant difference in the proportion of "aligned" responses was found between the No Change vs. One Change, and between the No Change vs. Alternating conditions (both at $p < .01$) in the Baseline 2 condition.

Similar results were found in the Random stream session. The main effect of Flash condition [$F(2,22) = 11.581$, $p < .001$], the main effect of Stream condition [$F(2,22) = 14.137$, $p < .001$], and the Flash × Stream interaction [$F(4,44) = 6.795$, $p < .001$] all reached statistical significance. The main effect of Travel Distance was marginally significant [$F(3,33) = 2.927$, $p = .048$], while pairwise comparisons showed that the four Travel Distance conditions did not differ significantly from each other. Specific comparisons showed that when the target disc and the flash were physically aligned (i.e., Aligned in Figure 2), the proportion of "aligned" responses was significantly lower in the No Change condition compared to the Random condition, whereas there was a significantly higher

proportion of "aligned" responses in the One Change condition compared to the Random condition. Similar to the Alternating session, no significant difference in response proportion was found among the three stream conditions in the Baseline 1 condition; there was a significant difference between the No Change vs. One Change, and between the No Change vs. Random stream conditions (both at $p < .01$) in the Baseline 2 condition.

The Baseline 1 condition appeared to more strongly eliminate the FLE than the Baseline 2 condition did. One possible reason for this difference is that, since the experiment was mixed with both baseline conditions, observers were aware that there was a condition where the target disc and the flash were obviously aligned and disappeared together (Baseline 1), possibly leading to lower confidence reporting alignment in the Baseline 2 condition, where there were two discs in different positions.

To summarize, the two sessions of the experiment replicated the finding that inserting a single change in an object's appearance during motion (i.e., the One Change stream) eliminated (or greatly attenuated) the FLE compared with the No Change stream. Furthermore, our experiments demonstrated that a motion stream where the object alternates colors or changes color randomly elicits some degree of FLE. These results imply that (a) the weakened FLE in the Alternating and Random streams may be due to impaired perceptual smoothness of motion compared to the No Change stream, and (b) elimination of FLE in the One Change stream may be due to the exceptionally high salience of the target disc during the second last frame of the motion; in the Alternating and Random streams, the disc may no longer be salient at the moment of flash presentation (cf. the One Change stream) because the surface feature is continuously changing throughout the disc's motion, leading to survival of FLE under these conditions.

To verify these two hypotheses, we conducted short control experiments with five additional observers, where they were requested to judge the smoothness of the motion stream or the salience of the target disc during the second last frame of the motion. In each trial in the sessions where smoothness of motion was evaluated, one No Change stream and one Alternating stream (or a Random stream in a separate session) were presented sequentially in a random order, and observers were asked to indicate which of the two motion streams exhibited greater smoothness in motion. There were 24 trials in each session. In most of the trials, the observers reported that the No Change stream was more smooth than either the Alternating and Random streams (average percentage of trials in which the No Change stream was judged as more smooth in comparison to the Alternating stream = 84.2%, Random stream = 84.2%). The sessions testing target disc salience during the second last frame of the motion were conducted in a similar manner, but a One Change stream was presented instead of a No Change stream. Observers were asked to judge which of two sequentially presented streams showed a more salient target disc during the second-last frame of the motion. The

observers judged the target disc to be more salient in the One Change stream compared to the Alternating (85.8%) and Random (90.8%) streams. The control experiments therefore suggest that both hypotheses (a) and (b) contribute to explain the reduced, but not eliminated, FLE in the Alternating and Random conditions.
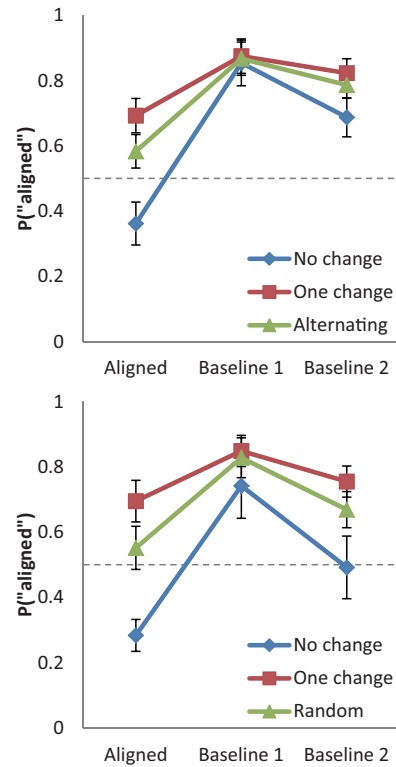

Figure 2: The average proportion of trials the observers reported alignment of the target disc and the flash stimuli for the Alternating (upper graph) and the Random (lower graph) sessions of the experiment; error bars represent the standard error of the mean.
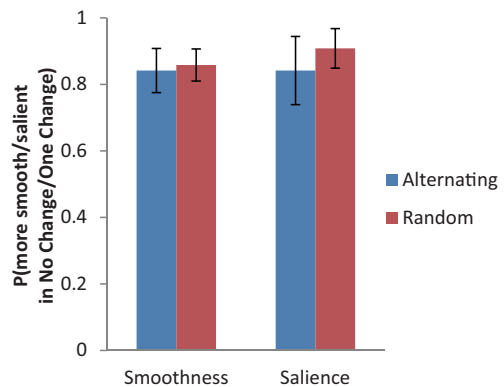

Figure 3: The average proportion of trials that the observers reported the motion of the No Change stream appears to be more smooth than the Alternating/Random stream (left panel), and that the target disc looks more salient at the second last frame in the One Change stream than the Alternating/Random stream (right panel); error bars represent the standard error of the mean.

Discussion

The results of the present study showed that under conditions where the target object kept changing color while moving in a uniform trajectory (i.e., Alternating and Random streams), a significant FLE was observed, although it was somewhat attenuated compared to the No Change condition. Furthermore, the results of the control experiments suggested that (a) the attenuation of the FLE under those conditions might be due to lower perceived motion smoothness compared to the No Change stream, and (b) the high salience of the target disc at the moment when the flash occurred might be responsible for the elimination of the FLE in the One Change stream. These results therefore suggest that smooth motion defined by unchanged physical surface features is not a necessary condition for the FLE. As long as the visual system identifies a single entity throughout motion, without a salient transient change (i.e., in the Alternating and Random streams), the observer can still perceive the FLE as in physically smooth motion. A highly salient change that occurs unexpectedly (i.e., in the One Change stream) is required to break continuity and cause the visual system to perceive multiple objects in the stream.

In the context of the FLE, the present results support the notion that spatiotemporal continuity dominates surface feature in processing object persistence (Mitroff & Alvarez, 2007). Although under some conditions, surface features can guide the mapping and updating of individual objects (Moore et al., 2010), spatiotemporal information is weighted more strongly in the computation of object persistence when both types of information are available (Tas, Dodd, & Hollingworth, 2012). A brain imaging study by Yi et al. (2008) also provides strong evidence that discontinued spatiotemporal trajectories can cause visually identical faces to be represented as different individual objects, in which the brain area involved was the most staunchly "featural" area of the ventral visual cortex. The determination of object persistence during object motion involves identifying the correspondence between objects over short periods. This is similar to how the visual system computes motion correspondence in the apparent motion phenomenon, in which solutions are sometimes needed to map multiple objects at one instance to multiple objects at other locations at the next instance; in such a case, spatiotemporal information plays an important role in assisting the visual system to arrive at an appropriate solution (Dawson, 1991).

From the results of the control experiments, we infer that the perceived smoothness of object motion and the salience of the transient change during motion mediate the magnitude and determine the survival of the FLE. Our results suggest that observers' subjective perception of smoothness was related to the magnitude of the FLE. In the Alternating and the Random conditions, observers reported less motion smoothness compared to the No Change condition, and the results of the main experiment indicated a significantly smaller FLE in the Alternating and Random conditions compared to the No Change condition. This is consistent with previous findings that perceived motion smoothness (i.e., sampling rate of the motion trajectory) and the magnitude of the FLE are highly correlated (Khurana, Nijhawan, & Watanabe, 1998). Such a relationship between motion smoothness and the magnitude of the FLE implies that the maintenance of object files that give rise to the FLE may be associated with smoothness of motion. In the context of the present study, the rapid change in physical features in the Alternating and Random streams impaired perceived motion smoothness, and the maintenance of object files was thus degraded, leading to a smaller FLE. Although the maintenance of object files was interrupted, the visual system still perceived only one object in the motion stream. In terms of the salience of the transient change at the time of the flash, our results are consistent with the proposal of Moore and Enns (2004) that the FLE depends on such a salient and unexpected change in smooth motion, as abrupt changes in object features may disrupt object representations (Moore et al., 2007). One possibility is that the salient and unexpected change in the One Change stream captured observers' attention. At the moment of flash onset, the abrupt change in the moving object increases attention and allows the moving object to be associated with the flash onset at its veridical position, sparing it from the FLE. In the Alternating and Random streams, since the color change was ongoing, any change would become less salient and less able to capture attention, thus preserving the FLE.

To summarize, the present study extended the results of previous FLE experiments (e.g., Moore and Enns, 2004) and showed that the FLE can occur in motion streams where the physical features of the moving object continuously change during motion. The magnitude and survival of the FLE was determined by perceived motion smoothness and the salience of the moving object at the time of the flash. We propose that a rapid change in a physical feature partially degrades the maintenance of the object file, but does not eliminate the overall percept of only one object in the motion stream. At the same time, it mostly reduces the salience of the disc at the moment of flash presentation. Future studies should focus on how attention at the moment of the flash influences the FLE.

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