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Manual control of the visual stimulus reduces the flash-lag effect

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Abstract

We investigated how observers' control of the stimulus change affects temporal aspects of visual perception. We compared the flash-lag effects for motion (Experiment 1) and for luminance (Experiment 2) under several conditions that differed in the degree of the observers' control of change in a stimulus. The flash-lag effect was salient if the observers passively viewed the automatic change in the stimulus. However, if the observers controlled the stimulus change by a computer-mouse, the flash-lag effect was significantly reduced. In Experiment 3, we examined how observers' control of the stimulus movement by a mouse affects the reaction time for the shape change in the moving stimulus and flash. Results showed that the control reduced the reaction time for both moving stimulus and flash. These results suggest that observers' manual control of the stimulus reduces the flash-lag effect in terms of facilitation in visual processing.

Keywords: Observers' control; Computer-mouse; Flash-lag effect; Reaction time

1. Introduction

This study uses the flash-lag effect to investigate the effects on visual perception of observer's manual control of visual stimulus. In many psychophysical studies of visual processing, observers passively viewed the visual stimuli, without any active involvement with or control of stimulus change. In most studies, the stimulus conditions were defined independently of the observer's action. Observer's active involvement with stimuli has been omitted from many of the experimental paradigms in psychophysics to keep the observers' situation constant and to collect stable data. While we have learned many things from these paradigms, we have relatively little knowledge about how the observer's control of stimuli affects visual processing. Yet in many real life situations, the observers manipulate and control the state of stimuli. This study investigates how the observer's manual control of stimuli affects visual perception, particularly temporal aspects of perception.

Several studies have demonstrated that the observers' active participation in the experimental task influences spatial aspects of visual perception. For example, studies of depth perception found that the observer's active movement changed the use of depth cues (Jones & Lee, 1981; Wexler, Panerai, Lamouret, & Droulez, 2001), and increased the apparent depth from motion parallax (Rogers & Graham, 1979). Sensitivity to depth perception from motion parallax varies with the velocity of active head movement (Ujike & Ono, 2001). Active exploration of three-dimensional objects in a computer display facilitates learning of the spatial structure of the objects compared to the passive observation of the same display (Harman, Humphrey, & Goodale, 1999; James, Humphrey, & Goodale, 2001). Active use of tools by hand facilitates perceptual learning of new spatial relationships between visual information and proprioceptive body representations for both normal observers (Maravita, Spence, Kennett, & Driver, 2002) and patients with hemianopia caused by a right hemisphere ischaemic stroke (Maravita, Husain, Clarke, & Driver, 2001, 2002). Studies of perceptual learning that used the prismatic adaptation paradigm have demonstrated that perceptual adaptation, as measured by

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the accuracy of judgment about the spatial location of the target, is greater in conditions of active observation than for passive observation (Held, 1965; Welch, 1978; Welch, Widawski, Harrington, & Warren, 1979). The results of these studies suggest that the active interaction of the observer with the visual stimuli affects the spatial aspects of visual perception, that is the perception of the spatial location, shape, and depth of objects. Some factors that are not involved in passive observation, such as proprioceptive information about the observer's body motion, may influence the processing of spatial information of objects. Most studies, however, were restricted to spatial aspects of visual perception. Research is lacking about how observers' active involvement affects temporal aspects of visual perception.

In order to examine the effects of the observer's active, self-controlled involvement with visual stimuli on the temporal aspect of visual perception, we measured the illusory flash-lag effect (Nijhawan, 1994). When a flash is presented physically aligned with a continuously moving stimulus, the flash is perceived in a lagged position relative to the moving stimulus (Nijhawan, 1994). Such a lag effect has been found not only for positional change, but also for changes in other visual attributes, such as changes in luminance, shape, and randomness (Sheth, Nijhawan, & Shimojo, 2000). Nijhawan and Kirschfeld (2003) demonstrated that there is a flash-lag effect related to the motor control system.

This flash-lag effect was initially explained as compensation for the intrinsic and inevitable delay of visual processing (e.g., Nijhawan, 1994, 2002). Other researchers have explained the flash-lag effect as related to the difference in latencies for the moving stimulus and the stationary flash (e.g., Bachmann, Luiga, Poder, & Kalev, 2003; Krekelberg & Lappe, 2001; Patel, Ogmen, Bedell, & Sampath, 2000; Whitney & Murakami, 1998; Whitney, Murakami, & Cavanagh, 2000). Or the effect may be explained as the misperception of the location of the moving stimuli induced by the flash stimulus that resets the motion integration (Eagleman & Sejnowski, 2000a, 2000b). Regardless of the explanation of the effect, the phenomenon is a consequence of temporal aspects of visual processing for stimulus motion, and other types of stimulus change. By investigating the effects of control of stimulus change on the flash-lag phenomenon, our goal is to increase knowledge about the function of control in visual processing, rather than to understand the basis of the illusory flash-lag effect.

The flash-lag effect has been investigated in experimental situations with automatic changes of a stimulus in a dimension (e.g., position, luminance, color, and distribution). What happens when the change is the consequence of the observer's action? How does the observer's control of the visual stimuli affect the temporal aspects of visual perception? In order to answer these questions, in the experiments in this study we compared the flash-lag effect (Experiments 1 and 2) and reaction times (Experiment 3) under conditions in which the changes in the stimulus in an attribute (position, or luminance) are automatic or related to the position of the computer-mouse which the observer manually controls.

2. Experiment 1

In the first experiment, we investigated whether the observer's control of the stimulus movement affects the flash-lag effect. The flash-lag effect was defined as the temporal lag between the moving stimulus and the flash that was required for the perception that the stimulus and flash are visually aligned at the same level.

2.1. Methods

2.1.1. Observers

The two authors and eight naive graduate students served as observers (age 21–38 years old). All of them had normal or corrected-to-normal visual acuity, and were right-handed. They had used personal computer with a computer mouse for at least 4 years.

2.1.2. Stimuli and apparatus

A personal computer (Apple Macintosh G4) presented stimuli on a 21″ display (Eizo T962, 75 Hz). The viewing distance was about 50 cm. The observer sat on a chair in front of a desk (80 cm in height), with the head fixed on a chin rest, and grasped the computer-mouse (Apple Pro Mouse M5769) with the right hand, where they could move it on the desk (Fig. 1). A computer keyboard (Sanwa Supply SKB-M1090H) was placed at the observers' left hand. The mouse and keyboard were connected to the computer by USB cables.

The center of the display was at the eye level of the observer. As a fixation point, a red square (19.1×19.0 arc min) was presented at the center of the display, on a black background (1.0 cd/m^2). A white horizontal line (334.3×2.4 arc min, 87.6 cd/m^2) was presented at the bottom or top of the display (about 15 arc deg above or below the fixation point) as the goal line for the moving stimulus. The moving stimulus and flash stimulus were white squares (19.1×19.0 arc min, 87.6 cd/m^2). The moving stimulus went upward or downward along a linear course at 2.6 arc deg right or left of the vertical centerline of the display. The length of the movement trajectory for the moving stimulus was 28.8 arc deg. The vertical position lag between the moving stimulus and the flash ranged from −76.0 to 76.0 arc min in 19.0 arc min steps (negative or positive values indicate that the position of the flash was behind or ahead of the moving stimulus, respectively). There were nine possible positions for the flash, and it ranged 4.5–7.0 arc deg above (for the upward movement) or below (for the downward movement) the fixation point. If this range was not enough for the veridical judgment at any position lag condition, the observer had another experimental session for the condition with the vertical position lag ranging from −152 to 152 arc min in 38.0 arc min steps.

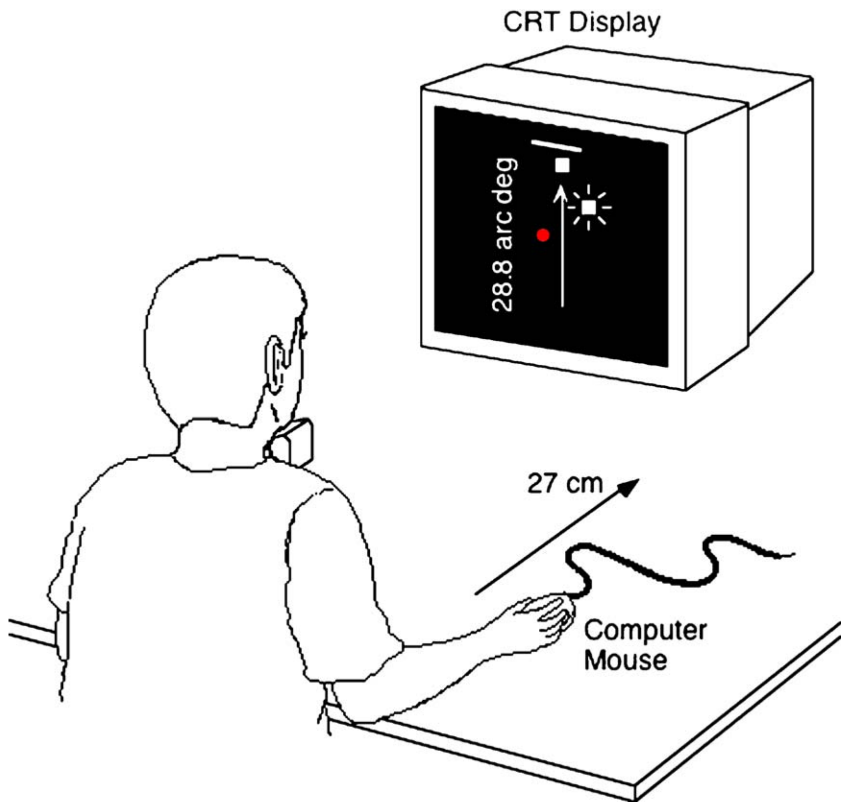

Fig. 1. Apparatus for Experiment 1. In the Manual condition, the computer-mouse controlled the vertical position of the moving stimulus.

2.1.3. Procedure

There were four observation conditions in which the moving stimulus was controlled in different ways. The first condition was the Manual condition. In this condition, the vertical position of the moving stimulus was controlled by the position of the computer mouse that the observers manually moved forward (away from the body) or backward (towards the body) on the desk. About 27.0 cm of mouse movement on the desk corresponded to 28.8 arc deg of vertical movement of the stimulus in the display. The observers could see their hands in the bottom of their visual field while viewing the fixation point. After the observers located the mouse at the start area on the desk that was indicated by the position of the goal line, they pressed the space key of the keyboard with their left hand to initiate the presentation of the moving stimulus. Observers were instructed to fixate on the red point, and to move the mouse for about 2 s from the start position to the goal line with a constant velocity while viewing the stimulus. If the movement took longer than 3200 ms or less than 1200 ms, the experimenter told the observer that the movement was out of the acceptable range, and that they should move the mouse faster or slower. In order to learn the acceptable mouse movement rate, and to learn that the mouse moved the stimulus, observers had a training session with at least 40 trials before the experimental trials until the observer's mouse movement was within the acceptable range (from 1200 to 3200 ms) in at least 10 consecutive trials. In the training session, observers moved the mouse while viewing the display that showed the moving stimulus with the fixation point and goal line but no flash stimulus. For all the sessions in this condition, the mean of the time that each observer took in moving the mouse from the start point to the goal ranged from 2133 to 2813 ms (for all observers, $M = 2436$, $SE = 65.4$). The mean velocity of the moving stimulus was recorded in each trial; the mean of the velocities for each observer ranged from 10.2 to 13.5 arc deg/s (for all observers, $M = 11.9$ arc deg/s, $SE = 0.32$).

The second condition was the Automatic condition. The sessions for this condition were conduced after the sessions for the Manual condition. Before the experimental sessions, the observers had at least 10 training trials until they felt that they understood the task. In this condition, the stimulus moved vertically with a constant velocity that was determined by the mean velocity from the Manual condition for each individual. At the beginning of each trial, the fixation point and goal line were presented, as in the Manual condition. After a random interval ranging from 1000 to 2000 ms after the observer pressed the space key, the stimulus started to move with a constant velocity.

The third condition was the Half-automatic condition. The sessions for this condition were conducted after the sessions for the Automatic condition. The instruction was the same as that in the Manual condition. Before the experimental sessions, observers had at least 10 training trials until they felt that they understood the task of the condition. In the Manual condition, observers might intentionally or unintentionally manipulate the mouse movement when the flash stimulus was likely to be presented in order to make the judgment easier, rather than moving the mouse with a constant velocity. To avoid this kind of manipulation, which might affect the flash-lag effect, in the Half-automatic condition, the stimulus moved automatically at a constant velocity after it passed the level of the fixation point. This constant velocity was the averaged velocity from the all trials in the Manual condition, the same as in the Automatic condition. Thus, the vertical position of the moving stimulus was determined by the mouse position as in the Manual condition until it reached the vertical level of the fixation point and then it was at a constant velocity as in the Automatic condition. The observer's task for this condition was the same as in the Manual condition. During the experimental sessions, only observer MI (one of the authors) noticed that the movement of the stimulus was automatic when the flash stimulus was presented.

The fourth condition was the Accompanied-hand-motion condition. The hand motion itself might affect the flash-lag effect, even though it did not control the stimulus movement by the mouse. This condition investigated the influence of moving the hand along with the stimulus movement on the flash-lag effect. The sessions for this condition were conducted after the sessions for the Half-automatic condition for seven of the observers. Observers viewed the same displays that were presented in the Automatic condition. The procedure was similar to that for the Automatic condition, except that observers were instructed to move the mouse to follow the moving stimulus. If the movement took longer than 2133 ms or shorter than 2333 ms, a high or low tone sound to indicate that the movement was out of the acceptable range, and that they should move the mouse slower (or faster). In order to learn the appropriate mouse movement, observers had at least 40 training sessions before the experimental trials until the observers' mouse movements were within the required range for at least 10 consecutive trials. In the training session, observers moved the mouse while viewing the same display that showed the moving stimulus with the fixation point and goal line but no flash stimulus. Three of the observers (MO, YM, and TK) needed additional sessions with the large range of the position lag (from −152 to 152 arc min) in the Accompanied-hand-motion condition. For these three observers, the data from the small and large ranges were combined in the analysis. Note that, when the flash was presented, the observers viewed the identical stimuli in the Automatic, Half-automatic, and Accompanied-hand-motion conditions.

There were five blocks for each of the conditions. In each block, 36 stimulus conditions (lag between the stimuli (9) × direction of the movement (2) × horizontal position of the moving stimulus (2)) were presented in random order. At the beginning of each trial, the fixation point and the goal line were presented. In accordance with the position of the goal line, the observers located the computer mouse at the start point on the desk. Then they pressed the space key on the keyboard. When the observers pressed the space key, the stimulus was presented at the bottom or top of the display (the start point for the next trial). In each condition, the observer's mouse control or key press started the vertical movement of the stimulus. After the moving stimulus passed the level of fixation point, the flash was presented for 13 ms (one frame) at one of the nine possible positions. After the moving stimulus reached the goal line, the observers reported whether the flash was above or below the moving stimulus. Sessions for each condition took about 30 min including the training sessions.

After all of the experimental sessions, the observers reported the easiest and most difficult conditions, and guessed the conditions in which their judgment was the most and least valid. They also reported how they felt during the sessions for each condition.

2.2. Results and discussions

We found no consistent effect related to the direction of movement, or the horizontal position of the moving stimulus. Therefore, the results of these conditions were combined in the following analyses.

Fig. 2A shows the results for one observer as an example. The vertical axis indicates the frequency in the trial in which the moving stimulus passed the level of fixation point. The horizontal axis shows the physical lag between the moving stimulus and the flash. Zero on the horizontal line indicates that the moving stimulus and flash were presented at the same vertical level. Therefore, the veridical judgment at this point was 50%. In this condition, the observer AMt judged that the moving stimulus passed the fixation point in about 80% of the trials in the Automatic condition and 100% in the Accompanied-hand-motion condition, while the judgments for the other two conditions were close to 50%.

Fig. 2B shows the flash-lag effect for each condition. The flash-lag effect was derived from the duration that each observer took in moving the mouse with the position lag that Probit analysis (Finney, 1971) determined as the 50% threshold for the response that the moving stimulus passed the level of the flash. Fig. 2C shows the means of the 50% thresholds in each condition from seven observers who took part in the four conditions.

Both Figs. 2B and C show that the flash-lag effect was larger for the Automatic condition than for the Manual condition and the Half-automatic condition. In particular, Fig. 2B shows that the flash-lag effect was reduced in the Manual and Half-automatic conditions for many observers while it was larger in these two conditions than in the Automatic condition for one observer (KS). The flash-lag effect was largest in the Accompanied-hand-motion condition (Fig. 2C).

We conducted a one-way repeated measure analysis of variance for the first three conditions using the data from the seven observers who took part in all the conditions (Fig. 2C). The main effect of the condition was significant ($F(3,18) = 16.553$, $p < .001$). Tukey's post hoc tests show

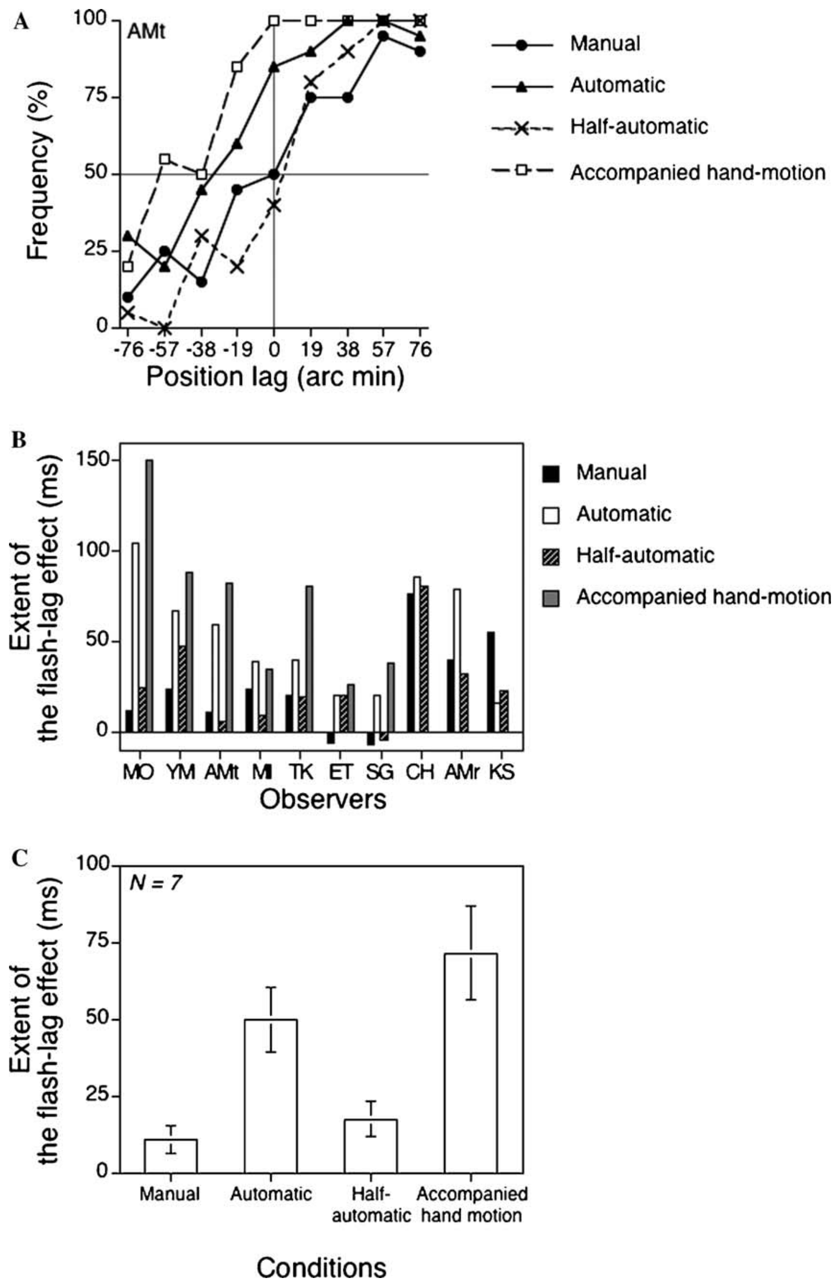

Fig. 2. Results of Experiment 1. (A) Example of an observer. (B) The 50% thresholds from each observer. Data for the Accompanied-hand-motion condition were from seven observers while data for the other three conditions were from all the observers. (C) Mean and *SE* of the 50% thresholds for the four conditions.

that the flash-lag effect in the Manual condition was significantly smaller than in the Automatic ($p < .01$) and Accompanied-hand-motion conditions ($p < .01$). Also, the flash-lag effect in the Half-automatic condition was significantly smaller than in the Automatic ($p < .05$) and Accompanied-hand-motion conditions ($p < .01$).

These results of the analysis indicate that observer's manual control of the stimulus movement in the Manual and Half-automatic conditions reduced the flash-lag effect. Although the observers viewed the same stimulus movement in the Half-automatic as in the Automatic condition when the flash was presented, there was a consistent difference in the flash-lag effect between these two conditions. Except for observer MI (one of the authors), none of the observers noticed that the stimulus movement was automatic when the flash stimulus was presented in the Half-automatic condition. These finding suggest that the reduction of the flash-lag effect in the Manual condition did not depend on the observers' manipulation of the mouse movement. The observers' awareness or mental set that they were controlling the stimulus movement did reduce the flash-lag effect. In the Accompanied-hand-motion condition, however, we could not find a reduction of the flash-lag effect; rather, the flash-lag effect increased. In this condition, none of the observers felt that they moved the stimulus. These results indicate that the hand motion itself does not reduce the extent of flash-lag effect if the observers did not have the mental set that they were controlling the stimulus movement. In this condition, some observers reported that they could not concentrate on the positional relationship between the two stimuli because they had to pay attention to the hand movement in order to move the mouse within the required time period. This division of attention might have been responsible for the larger extent of the flash-lag effect compared to the Automatic condition although there was not a statistically significant difference between these two conditions.

The averages of hand-motion-velocity from the seven observers in the Manual, Half-automatic, and Accompanied-hand-motion conditions were 11.19 cm/s ($SD = 0.96$), 10.77 cm/s ($SD = 0.55$), and 10.77 ($SD = 1.16$), respectively. There was no significant difference in the hand-motion-velocities among these conditions. This result suggests that there was no consistent difference in the hand-motion among these conditions, and supports the idea that the difference in the flash-lag effect among these conditions depends not on the hand-motion itself, but on the mental set that the observer controls the stimulus movement.

3. Experiment 2

As discussed in the Section 1, Sheth et al. (2000) demonstrated that the flash-lag effect was not restricted to stimulus movement. A similar effect has been found for successive changes in different attributes for visual perception. In the second experiment, we investigated whether the effects of control over the changes in stimulus attributes is restricted to position shift, which was investigated in Experiment 1. Can the effect be generalized to other changes in perceptual dimensions of the stimulus? In order to answer to this question, we investigated how the observer's control affects the flash-lag effect in terms of luminance change. We used the Manual condition in which the luminance of a stimulus changed with the mouse position controlled by observer's right hand, and the Automatic condition in which the luminance of the stimulus changed automatically at a constant rate.

3.1. Methods

3.1.1. Observers

The two authors and four naive graduate students served as observers. Five of them took part in the first experiment. Their age ranged from 21 to 38 years. All of them had normal or corrected to normal visual acuity.

3.1.2. Stimuli and apparatus

We used the same apparatus as used in Experiment 1. The setting of the equipment and the viewing distance were the same as in Experiment 1.

The luminance-change stimulus (57.3×56.9 arc min), whose luminance changes from 31.1 to 81.4 cd/m^2 (or from 81.4 to 31.1 cd/m^2), was presented 1.0 arc deg below or above the fixation point (19.0×19.1 arc min) that was located at the center of the display (Fig. 3). In order to control the luminance of the stimulus, we used a Gamma correction, and choose the range of color-look-up-table, which enabled us to change monotonically the luminance of the stimulus. The background was a 50% black/white random dot display. The size of the background dots was 2.4×2.4 arc min, and the luminance of the white and black dots were, respectively, 78.7 and 43.9 cd/m^2.

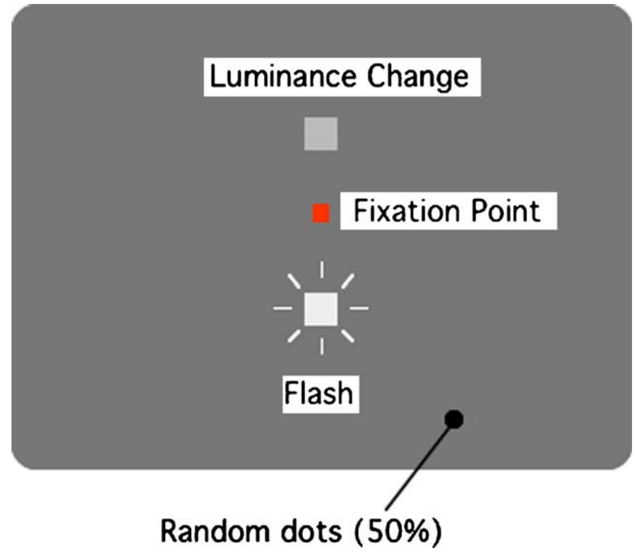

Fig. 3. Diagram of the stimulus configuration used in Experiment 2. In the Manual condition, the computer-mouse controlled the luminance of the stimulus.

During the luminance change, a flash (57.3×56.9 arc min) was presented for 13 ms, 1.0 arc deg above or below the fixation point. There were nine conditions for the luminance of the flash (ranging from 46.9 to 65.9 cd/m^2 in about 2.4 cd/m^2 steps).

3.1.3. Procedure

In the Manual condition, the luminance of the stimulus was controlled by the position of the computer-mouse that the observers manually moved forward (away from the body) or backward (towards the body) on the desk. About 27.0 cm of mouse movement corresponded to the luminance change from 31.1 to 81.4 cd/m^2 of the stimulus in the display. After the observers located the mouse at the start area on the desk that was indicated by the luminance of the stimulus, they pressed the space key of the keyboard with their left hand to initiate the trial. Observers were instructed to fixate on a red square, and to move the mouse in about two seconds from the start position to the goal line with a constant velocity. If the mouse movement took longer than 3200 ms or less than 1200 ms, the experimenter told the observer that the rate of movement was out of the acceptable range, and that they should move the mouse faster or slower. In order to learn the appropriate mouse movement, and also to learn that the mouse changed the luminance of the stimulus, observers had at least 40 training sessions before the experimental trials until the observers' mouse movements were within the acceptable range (from 1200 to 3200 ms) for at least 10 consecutive trials. For all trials in this condition, the means for the time that each observer took in moving the mouse from the start point to the goal ranged from 2200 to 2426 ms (for all observers, $M = 2348$ ms, $SE = 23.2$). The mean change rate of the luminance was recorded in each trial; the mean of the change rates for each observer ranged from 20.7 to 22.9 cd/m^2/s (for all observers, $M = 21.5$ cd/m^2/s, $SE = 0.28$).

The second condition was the Automatic condition, which was conducted after the sessions for the Manual condition. In this condition, the luminance of the stimulus changed at a constant rate that was determined by the mean change rate in the Manual condition for each individual. At the beginning of each trial, the fixation point and the stimulus were presented, as in the Manual condition. After a random interval ranging from 1000 to 2000 ms from the observer's key press, the stimulus started to change its luminance at a constant change rate. Just before the experimental sessions, observers had at least 10 training trials until they felt that they understood the task of the condition.

There were five blocks for each of the conditions. In each of the blocks, the 36 stimulus conditions (luminous lag between the stimuli (9) × direction of the luminance change (2) × vertical position of the luminance-change stimulus (2)) were presented in random order. In each trial, observers reported whether the flash was more luminous than the luminance-change stimulus. Each condition was presented 20 times in random order.

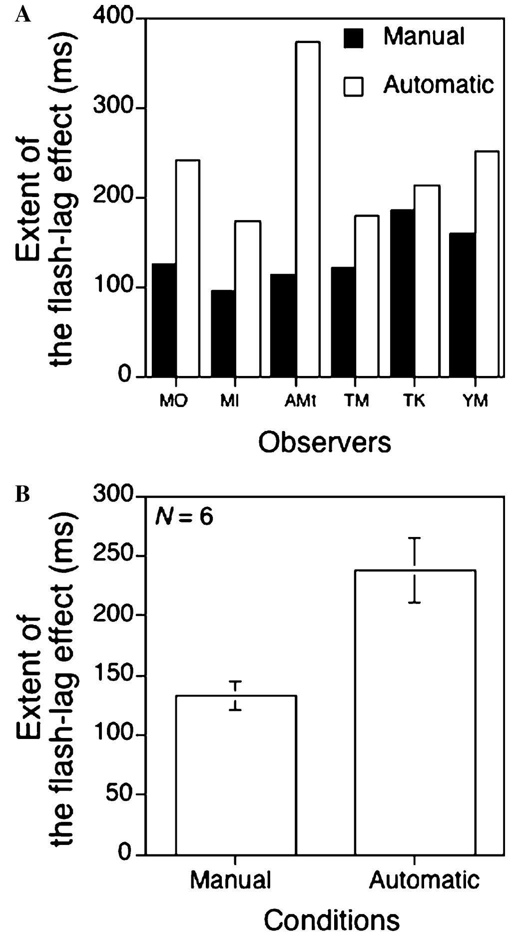

Fig. 4. Results of Experiment 2. (A) The 50% threshold from each observer. (B) Mean and *SE* of the 50% threshold for the two conditions.

3.2. Results and discussions

Fig. 4A shows the extent of the flash-lag effect in each condition, which was derived from the duration of each observer's mouse movements and the luminance lag that Probit analysis determined as the 50% threshold for the response that the luminance of the stimulus exceeded the luminance of the flash for each individual. Fig. 4B shows the mean of the flash-lag effect in each condition. Paired t test found a significant difference between the Manual and Automatic conditions ($t(5) = 3.167$, $p < .025$).

The flash-lag effects (Fig. 4B) in Experiment 2 were much larger than those reported by Sheth et al. (37 ms; 2002). We assume that this difference in the flash-lag effect for the luminance change is related to the differences in the procedures used in each study. For instance, the durations for the successive luminance change used in Experiment 2 (2100 ms) were much greater than in Sheth's study (830 ms). In their study, they found a similar flash-lag effect (394 ms) for the color change when they used a longer duration (from 2200 to 4400 ms), which was similar to our Experiment 2. These results suggest that the duration for the attribute change might influence the flash-lag effect. In addition, the differences in the background used in each study might affect the flash-lag effect. We used random dots as the background in Experiment 2, while they used a uniform background. Also, the luminance levels for the stimuli and background in present study were different from those in their study. Although the flash-lag effect in each study varied with various factors, we should note that there was a common finding in Experiments 1 and 2. For both motion and luminance changes, the observer's control of the stimulus changes reduced the flash-lag effect.

4. Experiment 3

How does the observer's control of the stimulus change reduce the flash-lag effect? Does the control preclude the visual system from compensating for the intrinsic delay of the visual processing of the stimulus change (cf. Nijhawan, 1994, 2002), or reduce the misperception of the changing stimulus (cf. Eagleman & Sejnowski, 2000a, 2000b)? Does it reduce the latency for the flash, which might cause the flash-lag effect (cf. Bachmann et al., 2003; Krekelberg & Lappe, 2001; Patel et al., 2000; Whitney & Murakami, 1998)? Or, does it affect the temporal aspect of visual processing in other ways? In order to address these questions, we investigated how the control of the stimulus movement affects the reaction time for the moving stimulus and flash in the third experiment.

4.1. Methods

4.1.1. Observers

Six observers who took part in Experiment 1 (including the two authors) participated in Experiment 3. All of them had normal or corrected to normal visual acuity.

4.1.2. Stimuli and apparatus

We used the same setting and apparatus as the first experiment. A red square (19.1×19.0 arc min) was presented at the center of the display as a fixation point on a black background ($1.0\,cd/m^2$). A white horizontal line was presented at the bottom or top of the display to show the goal of the moving stimulus. The flash stimulus consisted of two white squares (19.1×19.0 arc min) with a gap between them (38.2 arc min). At the beginning of each trial, the moving stimulus consisted of two white squares (19.1×19.0 arc min) with a gap between them (38.2 arc min). Before it reached to the goal line, the gap was filled in, so that the moving stimulus changed its shape from two squares to a white rectangle (76.4×19.0 arc min). The square in the moving stimulus that was nearer to the center of the display moved along a linear course at 2.6 arc deg right or left of the vertical center line of the display. The length of the movement trajectory for the moving stimulus was 28.8 arc deg. The vertical position lag between the moving stimulus and flash was specified in the same way as in Experiment 1.

4.1.3. Procedure

The procedure was the almost same as for the Manual and Automatic conditions in Experiment 1. The exception was that in each trial, the observers performed two tasks in this experiment as in some conditions in Khurana, Watanabe, and Nijhawan (2000). That is, in each trial, observers were required not only to report the flash position, but also to press the space key when they noticed the emergence of the flash stimulus or the shape change of the moving stimulus. After the moving stimulus passed the level of the fixation point, the moving stimulus changed its shape and the flash stimulus was presented. The timing for the shape change was randomized in each trial, and the timing was independent of the flash. The possible position for the shape change ranged from 4.5 to 7.0 arc deg above (for the upward movement) or below (for the downward movement) from the fixation point. The position for the flash was determined in the same way as in Experiment 1.

There were five blocks for each of the conditions (Manual and Automatic) and the targets for the reaction time measurements (shape change of the moving stimulus and flash). In each of the blocks, the 36 stimulus conditions were presented in random order (lag between the motion stimulus and flash $(9) \times$ direction of the movement $(2) \times$ horizontal position of the moving stimulus to the fixation point (2)). Before each block started, the observer was instructed which of the stimuli (shape change or flash), they were to detect in the block. In each trial, observers pressed the key by their left hand when they saw the shape change in the moving stimulus (shape-change detection task) or the flash stimulus (flash detection task). At the end of each trial, they judged whether the flash was ahead or behind the moving stimulus by pressing another key.

4.2. Results and discussions

Fig. 5A shows the mean and *SE* of the reaction time for each condition. The reaction time for the moving stimulus was shorter in the Manual condition than in the Automatic condition. Also the reaction time for the flash stimulus was shorter in the Manual condition than in the Automatic condition.

We conducted a 2×2 analysis of variance for repeated measures. The factors were the target stimulus for the reaction time measurement (moving stimulus or flash) and the condition (Manual or Automatic). The interaction of the two factors was not significant ($F(1,5) = 1.199$, $p > .10$) although the two main effects were significant: for the

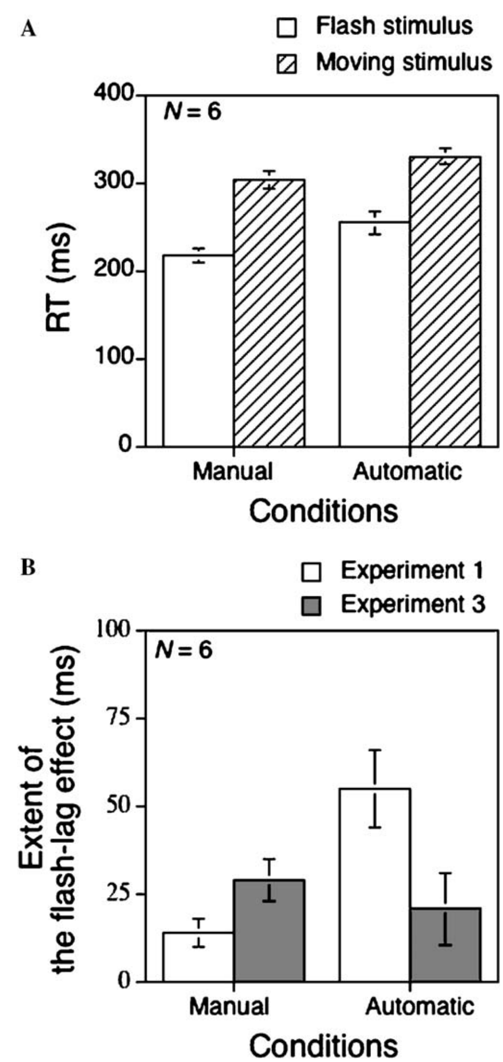

Fig. 5. Results of Experiment 3. (A) Mean and *SE* of the reaction time. (B) Mean and *SE* of the 50% threshold for the two conditions in which the observer was required to detect the flash. For the comparison, white bars show the data obtained in Experiment 1 from the same six observers.

target stimulus, $F(1,5) = 112.963$, $p < .001$; and for the condition, $F(1,5) = 8.364$, $p < .05$. These results show that, for both moving stimulus and flash the reaction time for the Manual condition was shorter than for the Automatic condition. Also the results show that the reaction time for the flash was significantly shorter than for the moving stimulus.

The results that the reaction time in the Manual condition were shorter than in the Automatic condition, and that there was no interaction of the two factors, suggest that the effect of the manual control is not restricted to either the moving stimulus or flash. Fig. 5A shows that the differences in the reaction times between the Manual and Automatic conditions are similar for both the moving stimulus and flash. These results imply that the observer's manual control facilitates the visual processing for both moving stimulus and flash.

The present finding that the reaction time for the flash was significantly shorter than for the moving stimulus is opposite to the results of previous studies, which found that the latency for the moving stimulus was shorter than that for the stationary stimuli (Purushothaman, Patel, Badell, & Ogmen, 1998; Whitney & Murakami, 1998; Whitney et al., 2000). Because the idea that the flash-lag effect is caused by latency difference between the moving stimulus and flash has been ruled out (Eagleman & Sejnowski, 2000a, 2000b), the present result that the reaction time for the moving stimulus was longer than for the flash does not conflict with the results in Experiments 1 and 2. However, we should discuss why we got longer reaction time for the moving stimuli than for the flash contrary to the previous studies (Purushothaman et al., 1998; Whitney & Murakami, 1998; Whitney et al., 2000). We suppose that detecting the shape change for the moving stimulus would be more difficult than detecting the flash in our trial. The results of the observers' judgments on whether the moving stimulus passed the level of the flash demonstrate that detecting the shape change was difficult. For the condition in which observers were required to detect the stimulus shape change, Probit analysis could not determine the position lag when observer saw the two stimuli at the same level because the range of the position lags used in the experiment was not great enough to get veridical responses for both the Manual and Automatic conditions. This result implies that the flash-lag effect was very large in this condition, or that observers' reactions were disturbed by the task procedure, regardless of the observation conditions. In contrast, for the condition where observers were required to detect the flash, Probit analysis could define the position lag when the observer saw the two stimuli at the same level. Fig. 5B shows the flash-lag effect derived from the position lag for the condition in which observers were required to detect the flash.

We compared the flash-lag effect between Experiments 1 and 3 since the same six observers took part in both experiments (Fig. 5B). We conducted a 2×2 analysis of variance for repeated measures. The factors were the experiments (Experiment 1 or 3) and the condition (Manual, or Automatic). The main effects of the experiments ($F(1,5) = 3.323$, $p > .10$) and conditions ($F(1,5) = 4.992$, $p > .05$) were not significant. The interaction of the two factors was significant ($F(1,5) = 11.808$, $p < .05$). Tukey's post hoc HSD test showed that the simple main effect of the experiment was significant only for the Automatic condition, and the simple main effect of the condition was significant only in Experiment 1 ($p < .05$). There was no significant difference in the flash-lag effect between the Manual and Automatic conditions in Experiment 3. These results suggest that the observer's attention to the flash in the Automatic condition reduced the flash-lag effect although the same attention in the Manual condition had no effect. The flash-lag effect in the Manual condition in Experiment 1 might have been already reduced to the minimum level, and no further reduction was possible in Experiment 3. Also, we found that, for both the Manual and Automatic conditions, attending to the moving stimulus caused the very large flash-lag effect in Experiment 3. The extent of the flash-lag effect would depend on the attention assigned to the flash. How attention to the stimuli affected the present results is discussed later.

5. General discussion

5.1. *Effects of active involvement*

All three experiments showed that the observers' participation in controlling the stimulus makes their perception more veridical. The results of Experiment 1 indicate that manual control of the stimulus movement reduces the illusory flash-lag effect. The results of Experiment 2 demonstrate that this reduced effect is not restricted to motion processing, and may be a more general characteristic of visual perception. The results of Experiment 3 suggest that the reduction in the illusory flash-lag effect is related to the facilitation of visual processing for both moving stimulus and flash. We propose that the active control of stimulus change functions to facilitate and speed up the processing for the whole visual field.

The flash-lag effect was inflated in the Accompanied-hand-motion condition in Experiment 1. This indicates that the hand motion itself is not a sufficient condition for the reduction of the flash-lag effect. If the hand motion is not related to the control of the stimulus, the flash-lag effect could be enhanced.

The results in the Half-automatic condition imply that the actual linkage between the hand motion and the visual stimulus change, and the proprioceptive information of the hand motion, is not responsible for the reduction of the flash-lag effect. Instead, those results suggest that the observer's awareness, or the mental set that the observer controls the stimulus-change is sufficient and necessary for the reduction of the flash-lag effect. This notion is compatible with the finding that subjective awareness of the discrepancy between visual and proprioceptive information was an important determinant in facilitating perceptual learning in the prismatic adaptation (e.g., Uhlarik, 1973).

Our aim was to understand how the observer's control of the stimuli affects the temporal aspects of visual processing, rather than to understand the mechanism that underlies the flash-lag effect. We cannot determine which of the major three explanations on the flash-lag effect is valid from the results of present three experiments. Our finding that the observers' control of the stimuli facilitates the visual processing for both the moving and flash stimuli is compatible with all of the proposed explanations.

5.2. Effects of attention

Some previous studies reported that attention influences the extent of the flash-lag effect (Baldo, Kihara, Namba, & Klein, 2002; Murakami, 2001; Shioiri, Yamamoto, & Yaguchi, 2002) while another study proposed that the flash-lag effect is independent of attentional deployment (Khurana et al., 2000). Many studies have demonstrated that attention may facilitate the visual processing (e.g., Hikosaka, Miyauchi, & Shimojo, 1993; Posner, 1980). It is plausible in the previous studies in which attention affected the flash-lag effect, that the attention shortened the processing time for both moving stimulus and flash (e.g., Baldo et al., 2002; Murakami, 2001; Shioiri et al., 2002). Consequently, the attention indirectly reduced the flash-lag effect as a result of reducing the processing time, just as the active control affected the processing for both motion stimulus and flash in present study. Attention could be one of the factors that modulate the extent of the flash-lag effect, as well as the dimension of stimulus change, and the active control that we examined in present study.

How was the attention involved in the difference in the flash-lag effect among the conditions in the present study? In Experiment 3, in the condition where the observer was required to detect the shape change of the moving stimulus, the flash-lag effect was greatly enhanced. This result implies that attending to the moving stimuli does not reduce the flash-lag effect. Moreover, all the observers reported that the Manual condition was more difficult than the Automatic condition because in the former condition they had to pay attention not only to the display but also to their own hand motion (Interestingly, all of the observers guessed that their performance would be more accurate in the Automatic condition than in the Manual condition although the opposite was true. As we have seen, they were wrong). These results suggest that the difference in the flash-lag effects between the Manual and Automatic conditions cannot be attributed to the difference in attentional resources assigned to the flash in these conditions. We are proposing that the smaller flash-lag effect (Experiments 1 and 2) and the shorter reaction time (Experiment 3) for the Manual condition are attributed mainly to the facilitation of visual processing as a result of the manual control, rather than differences in the assignment of attention to either stimulus.

We are not saying that the assignment of attention had no influence on the differences in the flash-lag effect among the conditions in the present experiments. The observers reported that the Accompanied-hand-motion condition was the most difficult of the conditions in Experiment 1 because they had to concentrate not only to judge the relationship between the moving stimulus and flash, but also to be careful to follow the moving stimulus, and to keep their hand motion within a narrowly restricted range. We expected that the attentional resource assigned to the stimuli would be the least in this condition among all the conditions in Experiment 1. All of the observers correctly guessed that their accuracy would be the worst in this condition. These results are compatible with previous studies where taking away attention from the visual stimuli enhanced the flash-lag effect (Baldo et al., 2002; Murakami, 2001; Shioiri et al., 2002). Moreover, we found a large flash-lag effect in attending to the shape change of the moving stimulus in Experiment 3. The attentional resource assigned to the flash should be the least in this condition in Experiment 3. These results indicate that taking away visual attention from flash would greatly enhance the flash-lag effect.

5.3. Function of the hand

Several studies have reported that the observers' hands play an important role in the cross-modal interaction between vision and proprioception. Clark, Tremblay, and Ste-Marie (2003) measured the motor evoked potentials (MEP) for the passive observation in which observers viewed the scene of hand motion presented on a monitor display without moving their own hand, and for the active observation in which observer moved their hand to imitate the presented hand motion. They found that the MEP for the passive observation was similar to that for the active observation. Voluntarily manipulating a tool by hand enables the perceptual learning of the spatial relationship between the vision and proprioception (Maravita et al., 2001; Maravita, Clarke, Husain, & Driver, 2002; Maravita & Spence et al., 2002). Even for a stationary hand, the visual information affects the judgment based on the proprioception for the spatial location of that hand (Pavani, Spence, & Driver, 2000). In adaptation to the continuous wearing of left–right reversing spectacles, the hand may play a key role to reconstruct spatial representation (Sekiyama, Miyauchi, Imaruoka, Egusa, & Tashiro, 2000). These studies indicate that vision and proprioception interact in the movement of hands, and that the interaction related to the hand motion facilitates the spatial aspect of visual processing.

Does the hand motion have special and unique function to modulate visual processing? It is true that the relationship between vision and hand motion has several special and unique points. For example, the hand motion may be related to the changes of some specific visual stimuli in the visual field while the head motion and eye movement generate the flow of the whole visual field. Although the motion of the other body parts, such as arms, legs, or trunk, may be related to the specific visual stimuli, the motion of those body parts, compared to the hand motion, would be less frequently related to the tasks that involve intentional control of objects. Therefore, it is plausible that the hand has a special function in the cross-modal interaction between vision and proprioception. However, for the spatial aspect of the visual processing, previous studies have demonstrated that the facilitating effects of active observation are not restricted to the hand motion. For example, the hand was not involved in some previous studies demonstrating the effects of active observation on spatial aspects of perception (e.g., Jones & Lee, 1981; Rogers & Graham, 1979; Ujike & Ono, 2001; Wexler et al., 2001). After a few days of wearing left–right reversing prisms, drastic adaptive changes were found on tasks in which the observer's hand manipulation was not involved, such as depth reversal in stereogram observation (Ichikawa & Egusa, 1993; Ichikawa et al., 2003; Shimojo & Nakajima, 1981), and the hemispheric activation in area V1 and MT/MST in observing stimulus patterns presented to the ipsilateral visual field (Miyauchi et al., 2004). These studies imply that the hand motion is not a necessary condition for the facilitation of the visual processing, and that the effect of active movement on the spatial aspects of perception can be generalized for movement at various body parts.

We should ask whether the hand has any special and unique function to affect the temporal aspect of visual processing. Future investigation is required to understand whether the facilitating effect of the active observation on the temporal aspect of the visual processing is specific to the hand motion, or whether that effect is general for active observation with cross-modal interaction involving different body parts. The subjective representation of the hand itself may affect the tactile perception of temporal order even if there is no relevant visual information (Yamamoto & Kitazawa, 2001a, 2001b). These studies together with present results, suggest that the hand has an important function to modulate the temporal aspects in perception.

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References

Bachmann, T., Luiga, I., Poder, E., & Kalev, K. (2003). Perceptual acceleration of objects in stream: Evidence from flash-lag displays. *Consciousness and Cognition, 12*, 279–297.

Baldo, M. V. C., Kihara, A. H., Namba, J., & Klein, S. A. (2002). Evidence for an attentional component of the perceptual misalignment between moving and flashing stimuli. *Perception, 31*, 17–30.

Clark, S., Tremblay, F., & Ste-Marie, D. (2003). Differential modulation of corticospinal excitability during observation, mental imagery and imitation of hand actions. *Neuropsychologia, 42*, 105–112.

Eagleman, D. M., & Sejnowski, T. J. (2000a). Motion integration and postdiction in visual awareness. *Science, 287*, 2036–2038.

Eagleman, D. M., & Sejnowski, T. J. (2000b). Reply to Patel et al. *Science, 290*, 1051.

Finney, D. J. (1971). *Probit Analysis*. Cambridge: Cambridge University Press.

Harman, K. L., Humphrey, G. H., & Goodale, M. A. (1999). Active manual control of object views facilitates visual recognition. *Current Biology, 9*, 1315–1318.

Held, R. (1965). Plasticity in sensory-motor systems. *Scientific American, 213*, 84–94.

Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993). Focal visual attention produces illusory temporal order and motion sensation. *Vision Research, 33*, 1219–1240.

Ichikawa, M., & Egusa, H. (1993). How is depth perception affected by long-term wearing of left–right reversing spectacles? *Perception, 22*, 971–984.

Ichikawa, M., Kimura, T., Egusa, H., Nakatsuka, M., Amano, J., Ueda, T., & Tashiro, T. (2003). Modification of depth and distance perception caused by long-term wearing of left–right reversing spectacles. *Perception, 32*, 131–153.

James, K. H., Humphrey, G. K., & Goodale, M. A. (2001). Manipulating and recognizing virtual objects: Where the action is. *Canadian Journal of Experimental Psychology, 55*, 111–120.

Jones, R., & Lee, D. (1981). Why two eyes are better than one: The two views of binocular vision. *Journal of Experimental Psychology: Human Perception and Performance, 7*, 30–40.

Khurana, B., Watanabe, K., & Nijhawan, R. (2000). The role of attention in motion extrapolation: Are moving objects 'corrected' or flashed objects attentionally delayed? *Perception, 29*, 675–692.

Krekelberg, B., & Lappe, M. (2001). Neuronal latencies and the position of moving objects. *Trends in Neurosciences, 24*, 335–339.

Maravita, A., Clarke, K., Husain, M., & Driver, J. (2002). Active tool use with the contralesional hand can reduce cross-modal extinction of touch on that hand. *Neurocase, 8*, 411–416.

Maravita, A., Husain, M., Clarke, K., & Driver, J. (2001). Reaching with a tool extends visual-tactile interactions into far space: Evidence from cross-modal extinction. *Neuropsychologia, 39*, 580–585.

Maravita, A., Spence, C., Kennett, S., & Driver, J. (2002). Tool-use changes multimodal spatial interactions between vision and touch in normal humans. *Cognition, 83*, B25–B34.

Miyauchi, S., Egusa, H., Amagase, M., Sekiyama, K., Imaruoka, T., & Tashiro, T. (2004). Adaptation to left–right reversed vision rapidly activates ipsilateral visual cortex in humans. *Journal of Physiology—Paris, 98*, 207–219.

Murakami, I. (2001). The flash-lag effect as a spatiotemporal correlation structure. *Journal of Vision, 1*, 126–136.

Nijhawan, R. (1994). Motion extrapolation in catching. *Nature, 370*, 256–257.

Nijhawan, R. (2002). Neural delays, visual motion and the flash-lag effect. *Trends in Cognitive Sciences, 6*, 387–393.

Nijhawan, R., & Kirschfeld, K. (2003). Analogous mechanisms compensate for neural delays in the sensory and the motor pathways: Evidence from motor flash-lag. *Current Biology, 13*, 749–753.

Patel, S. S., Ogmen, H., Bedell, H. E., & Sampath, V. (2000). Flash-lag effect: Differential latency, not post diction. *Science, 290*, 1051.

Pavani, F., Spence, C., & Driver, J. (2000). Visual capture of touch: Out-of-body experiences with rubber gloves. *Psychological Science, 11*, 353–359.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*, 3–25.

Purushothaman, G., Patel, S. S., Badell, H. E., & Ogmen, H. (1998). Moving ahead through differential visual latency. *Nature, 396*, 424.

Rogers, B. J., & Graham, M. E. (1979). Motion parallax as an independent cue for depth perception. *Perception, 8*, 125–134.

Sekiyama, K., Miyauchi, S., Imaruoka, T., Egusa, H., & Tashiro, T. (2000). Body image as a visuomotor transformation device revealed in adaptation to reversed vision. *Nature, 407*, 374–377.

Sheth, B. R., Nijhawan, R., & Shimojo, S. (2000). Changing objects lead briefly flashed ones. *Nature Neuroscience, 3*, 489–495.

Shimojo, S., & Nakajima, Y. (1981). Adaptation to the reversal of binocular depth cues: Effects of wearing left–right reversing spectacles on stereoscopic depth perception. *Perception, 10*, 391–402.

Shioiri, S., Yamamoto, K., & Yaguchi, H. (2002). Effect of attention on flash lagging. *Journal of Vision, 2*, 27a.

Uhlarik, J. J. (1973). Role of cognitive factors on adaptation to prismatic displacement. *Journal of Experimental Psychology, 98*, 223–232.

Ujike, H., & Ono, H. (2001). Depth thresholds of motion parallax as a function of head movement velocity. *Vision Research, 41*, 2835–2843.

Welch, R. B. (1978). *Perceptual Modification*. New York: Academic Press.

Welch, R. B., Widawski, M. H., Harrington, J., & Warren, D. H. (1979). An examination of the relationship between visual capture and prism adaptation. *Perception & Psychophysics, 25*, 126–132.

Wexler, M., Panerai, F., Lamouret, I., & Droulez, J. (2001). Self-motion and the perception of stationary objects. *Nature, 409*, 85–88.

Whitney, D., & Murakami, I. (1998). Latency difference, not spatial extrapolation. *Nature Neuroscience, 1*, 656–657.

Whitney, D., Murakami, I., & Cavanagh, P. (2000). Illusory spatial offset of a flash relative to a moving stimulus is caused by differential latencies for moving and flashed stimuli. *Vision Research, 40*, 137–149.

Yamamoto, S., & Kitazawa, S. (2001a). Reversal of subjective temporal order due to arm crossing. *Nature Neuroscience, 4*, 759–765.

Yamamoto, S., & Kitazawa, S. (2001b). Sensation at the tips of invisible tools. *Nature Neuroscience, 4*, 979–980.