

RICE UNIVERSITY

**Motion Asymmetry Theory:
A Unifying Account of Motion/Position Illusions?**

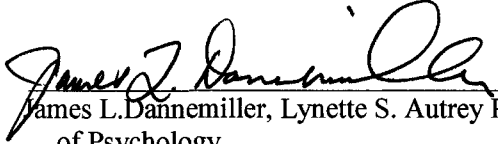
by

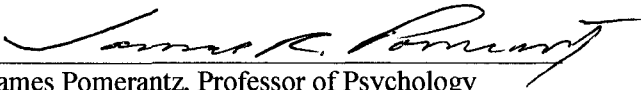
Chen Sun

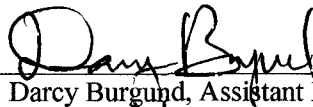
A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

Master of Arts

APPROVED, THESIS COMMITTEE:


James L. Dannemiller, Lynette S. Autrey Professor
of Psychology


James Pomerantz, Professor of Psychology


Darcy Burgund, Assistant Professor of
Psychology

HOUSTON, TEXAS

JANUARY 2008

UMI Number: 1455289

INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

UMI[®]

UMI Microform 1455289

Copyright 2008 by ProQuest LLC.

All rights reserved. This microform edition is protected against unauthorized copying under Title 17, United States Code.

ProQuest LLC
789 E. Eisenhower Parkway
PO Box 1346
Ann Arbor, MI 48106-1346

ABSTRACT

Motion Asymmetry Theory: A Unifying Account of Motion/Position Illusions?

by

Chen Sun

The motion/position illusion refers to phenomena in which an object is systematically mislocalized in the presence of motion. The object's location is usually misperceived in the direction of motion. We tested the hypothesis that motion asymmetry theory could account for the flash-lag illusion, and determined its potential as a unifying theory of motion/position illusions. We showed that the flash-lag illusion could not be explained by the theory based on two results. First, we found that it was the trailing edge that was primarily misperceived in the direction of motion, rather than the leading edge predicted by the theory. Second, we found that the size of the perceived centroid shift of the moving object produced by edge misperception was not sufficient to explain the magnitude of the flash-lag illusion. Our results suggest that the flash-lag illusion involves more than simply the mislocalization of the edges of a moving object.

KEY WORDS: flash-lag illusion, motion asymmetry theory, perceived centroid shift, leading/trailing edge misperception

ACKNOWLEDGMENTS

I appreciate the help and guidance of my advisor Dr. James L. Dannemiller throughout this study. My other committee members Dr. Darcy Burgund and Dr. James Pomerantz also provided helpful comments and suggestions regarding the experiment design. I want to thank Dr. David Eagleman for his suggestions and comments on the results. I also want to thank my lab members Jennifer Boyer and Melanie Lunsford Hamel and former lab member Magdalena G. Grohman for their support and valuable suggestions.

TABLE OF CONTENTS

INTRODUCTION.....	1
CONTROL EXPERIMENT	
METHOD	
Participants.....	13
Apparatus.....	13
Stimuli.....	13
Procedure.....	15
RESULTS.....	16
EXPERIMENT 1	
METHOD	
Apparatus & Stimuli.....	20
Procedure.....	25
RESULTS.....	26
EXPERIMENT 2	
METHOD	
Stimuli & Procedure.....	29
RESULTS.....	30
EXPERIMENT 3	

METHOD	v
Apparatus & Stimuli.....	36
Procedure.....	36
RESULTS.....	40
DISCUSSION.....	47
CONCLUSION.....	51
REFERECENCES.....	52

Introduction

The motion/position illusion refers to the systematic errors made in localizing an object when motion information is present. The positions of objects are usually misperceived offset in the direction of motion. There are many examples of such illusions. The “fine-grain motion illusion”, for example, refers to the phenomenon that in the peripheral visual field, when two nearby points are successively stimulated, observers perceive a movement extending farther than the distance between the two points (Thorson, Lange, & Biederman-Thorson, 1969).

The “flash-lag illusion” is another example of the motion/position illusion. This refers to the phenomenon that a continuously moving object is perceived to lead a flashed object in space, and the flash appears to lag behind the moving object, even when they are physically aligned at the instant of the flash (See Figure 1) (Nijhawan, 1994; Khurana & Nijhawan, 1995). Similarly, a misperception of the location at the onset of movement is termed as the “Fröhlich effect”, and a misperception of the vanishing point of a moving object is termed as “representational momentum” (See Figure 1b&c; Kirschfeld & Kammer, 1999; Müsseler, Stork, & Kerzel, 2002; Hubbard, 1995).

Positional misperception is not only limited to objects that are in real motion. Stationary objects can be also influenced by motion information that is present in various forms. One example is reported by De Valois and De Valois (1991) using stationary Gabor patches. In their study, they used stationary windows with drifting texture inside and found that the perceived positions of the windows were biased by the movement within them. They asked subjects to judge the alignment of three stationary Gabor patches. The Gabor is simply a windowed grating with the window imposing a gradual

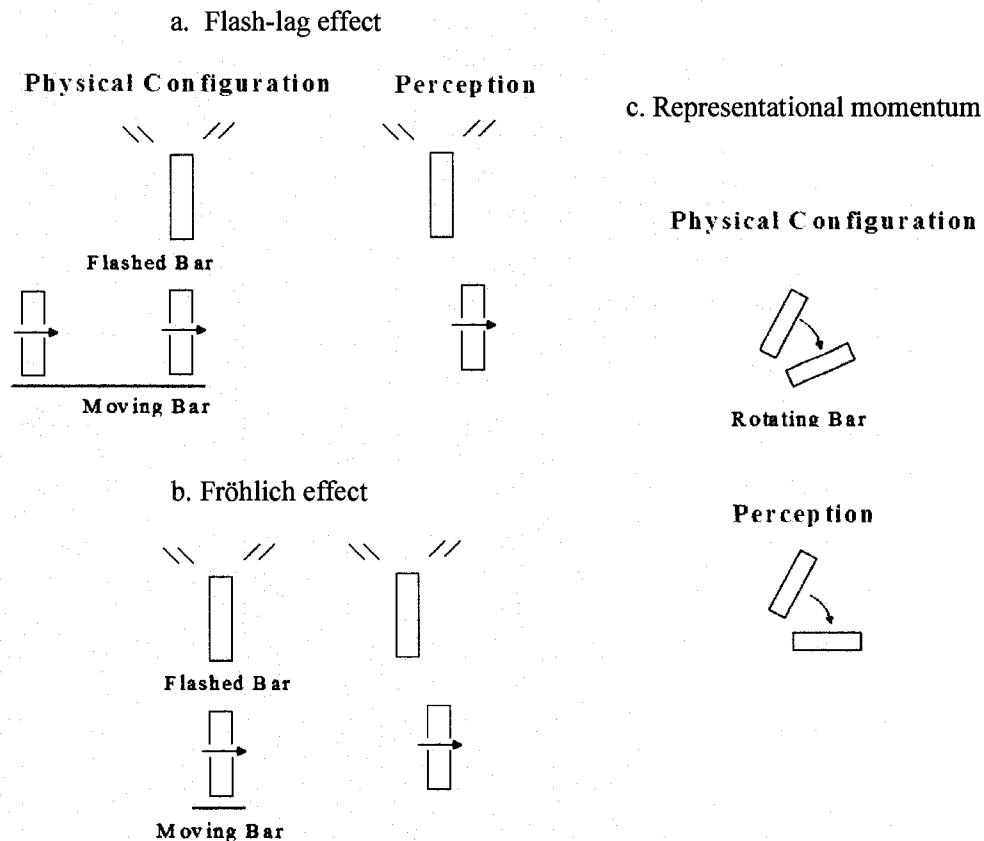


Figure 1a. The “flash-lag effect”. A bar moves from the left to right, as the arrow indicates. As the bar moves, an identical bar flashes above it. The figure on the left shows that, at the instant of flashing, the bar is presented as physically aligned with the moving object. The figure on the right shows the perceived position of the bar relative to the flashed object. The moving bar is misperceived as being ahead of the flashed stimulus in the direction of its motion. *Figure 1b.* The “Fröhlich Effect”. The figure on the left shows that a bar is flashed to be physically aligned with the onset position of a moving bar. The moving bar travels from the left to the right, indicated by the arrow. The figure on the right shows that the position of the moving stimulus’ onset is misperceived in the direction of its motion. *Figure 1c.* The “Representational Momentum” illusion. A bar rotates as the arrow indicates. The final position of the bar is perceived to be offset in the direction of rotation. The figure on the top shows the final physical offset position of the bar and the figure on the bottom shows the perceived position of the final position of the rotating bar.

decrease in the contrast of the grating away from its center. The gratings in the top and bottom Gabor patches drifted in the same directions, and the grating in the middle patch drifted in the direction opposite to the direction of the top and bottom patches. They found that the physically aligned Gabors were perceived to be misaligned with the middle patch that was perceived to be offset in the direction of its grating's drift relative to the top and bottom patches (See Figure 2). Another example is reported by Ramachandran and Anstis (1990). In their experiment, they formed a physically square configuration with four stationary windows defined by kinetic edges. Each window was sparsely filled with random gray dots that continually moved behind the window. The dots in the top windows moved toward the midline, while those in the bottom windows moved away from the midline. The configuration was perceived to be trapezoidal in shape, because the locations of the windows were misperceived to be offset in the direction of their internal motion (See Figure 3).

Even the positions of remote stationary objects can be influenced by motion information that is present in distant regions of the visual field. In Whitney's and Cavanagh's study (2000), a pair of horizontally aligned stationary lines was flashed on either side of a rotating radial grating. The lines, influenced by the remote motion of the grating, appeared misaligned and displaced in opposite directions consistent with the motion nearest to each line (See figure 4).

All these illusions provide evidence of the erroneous judgment of object location, when motion is present. The phenomenon of misperceiving the locations of moving objects is theoretically interesting given the fact that humans are typically very good at perceiving spatial position with stationary objects. Vernier acuity, the ability to detect

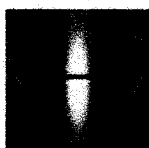
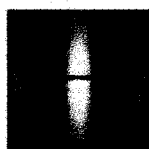
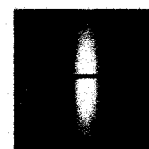
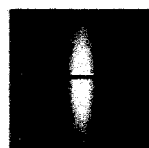
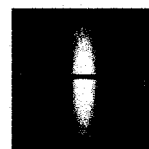
Physical Configuration**Perception**

Figure 2. Illustration of the illusion found in De Valois and De Valois (1991). The figure on the left shows the physical configuration of the stimuli. Three Gabor windows are physically aligned, filled with drifting gratings inside. The Gabors on top and bottom drift in the same direction, and the one in the middle drifts in the opposite direction. The figure on the right shows the perception of the locations of the Gabors. The three Gabors are perceived as misaligned, because each Gabor is misperceived to be offset in the direction of its motion.

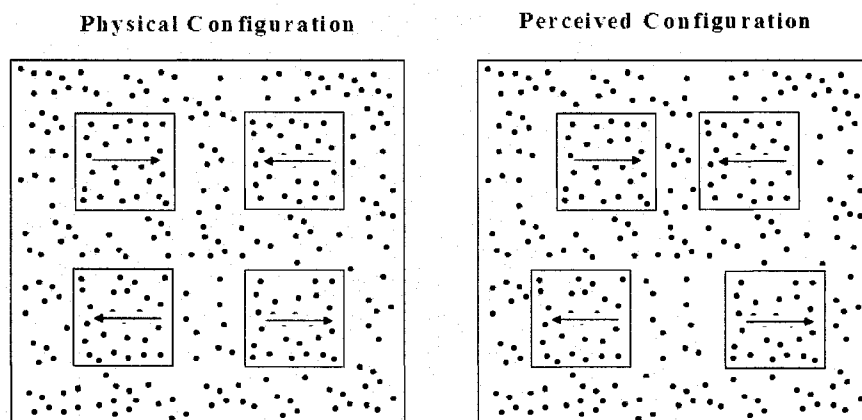


Figure 3. Illustration of the illusion found in Ramachandran and Anstis (1990). The figure on the left is the physical configuration of the stimuli. The windows are stationary, filled with moving dots. The edges of the windows are defined only by the movement of the dots, and when the motion stops, the edges disappear. The dots in the top windows drift toward the midline and those in the bottom windows drift away from the midline. The four windows form a physical square shape. The figure on the right is what the configuration actually looks like. The positions of the windows are misperceived as displacing toward the direction of the motion. As a result of this, the four windows look trapezoidal in configuration.

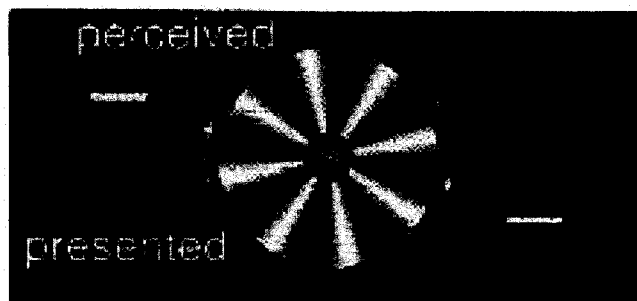


Figure 4. Illustration of the illusion found in Whitney and Cavanagh (2000). Two lines aligned on either side of a rotating radial grating are flashed. The darker lines show the physical positions of the flashed lines. However, those two lines are perceived misaligned and offset toward the rotating motion on their respective sides. The brighter lines show the perceived positions of the flashed lines. The line on the left side is shifted up and that on the right side is shifted down in the direction of motion.

spatial misalignment, is also called “hyperacuity” due to the high resolution of misalignment detection. The visual system is able to detect misalignments even smaller than the distance between neighboring photoreceptors in the retina (Westheimer, 1975). Thus, it is puzzling why relative position is misperceived with moving objects.

Two major classes of mechanisms - temporal and spatial - have been proposed to account for motion/position illusions (Whitney, 2002). The temporal account suggests that “perceptual latency” is an important factor. It is the time at which the objects are perceived that determines their perceived relative positions. For example, according to the temporal account, the “flash-lag effect” can be explained by different perceptual latencies for moving and flashed objects. Flashed objects take longer to perceive; therefore, by the time the flashed object is perceived, the moving object has moved forward to a different position.

The temporal account is supported by studies showing that objects with different brightnesses (causing different perceptual latencies) appear to move with the brighter one leading, even though they are physically aligned. However, it is contradicted by other evidence. Eagleman and Sejnowski (2005) suggest that latency differences alone do not account for the flash-lag effect. In their experiment, they designed two conditions: a “5-station” condition and a “2-station” condition. The conditions varied in the number of positions that a moving object could be seen over a 67ms period, starting from the position where the moving object was aligned with the flashed object (See Figure 5.). In the “2-station” condition, the moving object traveled the same distance as it did in the “5-station” condition in the same amount of time, but it was invisible at the 2nd, 3rd and 4th positions. The temporal account predicts that the moving object should be perceived at

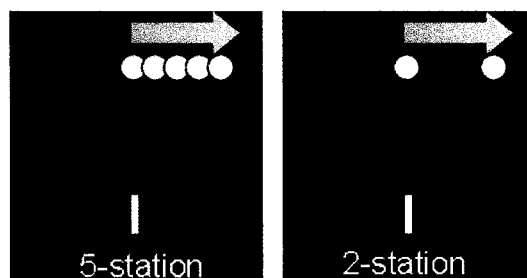


Figure 5. Illustration of the experiment schema in Eagleman and Sejnowski (2007). The figure on the left is the “5-station” condition, in which the moving dot is presented at 5 positions over 67ms, after the instant of the flash. The figure on the right illustrates the “2-station” condition, in which the moving dot travels the same distance during the same time, but it is only present at 2 positions. The dot is invisible at the 2nd, 3rd and 4th positions.

real positions, but just misaligned in time. Therefore, in the “2-station” condition, there should be either no flash-lag effect or the moving object should be misperceived at the second position. However, the results showed that there was a flash-lag effect in both conditions, and the moving object in the “2-station” condition was misperceived at positions where it was not physically presented.

The temporal account also faces difficulties accounting for several other motion/position illusions. For example, in De Valois and De Valois (1991) and also in Ramachandran’s and Anstis’ (1990) study, the stimuli used were identical except for the moving directions. Therefore, there should not be any perceptual latency difference among stimuli that could lead to the perceived misalignment.

The second class of accounts involves spatial mechanisms. A moving object is perceived ahead of its real position in the direction of its motion because of the influence of the motion information (Fu, Shen and Dan, 2001; Eagleman and Sejnowski, 2007). The way our visual system computes the position of an object when motion is present is by combining its on-going movement with instantaneous position information. There is one important question concerning this spatial account: how exactly does the motion information interact with the position information of a moving object?

Tsui, Khoo and Hayes (2007) proposed a motion asymmetry theory, asserting that motion signals bias the perceived location of a moving object’s spatial centroid. The perceived positional shift is not a result of shifting the position of a whole object along the direction of motion (Figure 6). Instead, it is an asymmetrical influence of the motion signals on the perceived positions of the leading and trailing edges that produces a shift of the perceived location of an object’s centroid. The perceived location of the leading

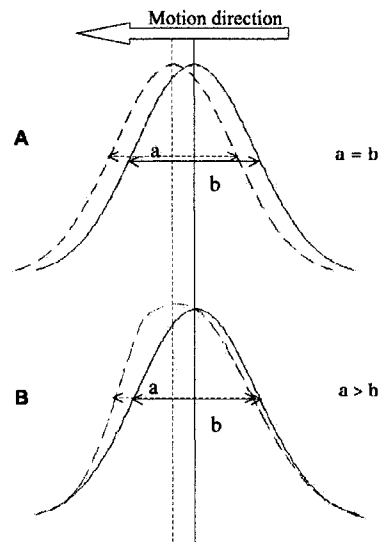


Figure 6. Illustration of the possible ways motion signals influence the perceived position of a pattern. A. The whole pattern shifts in the direction of motion. B. The perceived position of the leading edge of the pattern shifts further away than that of the trailing edge, leading to centroid shift in the direction of motion.

edge of a moving object is hypothesized to be more influenced by motion compared to the trailing edge. This proposal was supported by studies using stationary Gabor patches with sinusoidal gratings drifting inside (Tsui et al, 2007). They found that the leading edge of a Gabor pattern was more influenced by motion signals compared to the trailing edge based on two results: 1) The size of Gabor pattern was perceived to be fatter than its physical size, because that the leading edge was perceived to be elongated in the direction of motion by a larger amount than the trailing edge; 2) The magnitude of the shift in the leading edge increased monotonically with speed, whereas the magnitude of the shift in the trailing edge did not.

The above proposal is very intriguing and potentially informative regarding the process by which motion signals and position information interact. However, this proposal has only been tested in the context of Gabor patches. Will it also apply to other motion/position illusions, for example, the “flash-lag effect?” A direct generalization is not guaranteed because there are at least two major differences between the two experimental paradigms. First, the type of motion is different. The Gabor windows did not move. The motion information that influences the perceived location of the Gabor comes from texture moving within the stationary window. On the other hand, in the flash-lag effect, the misperception of the moving object is due to its real motion. It is possible that in the Gabor paradigm, the misperception of size is partly due to motion adaptation mechanisms. In the Gabor paradigm, the motion information falls consistently on the same part of the retina when fixation is maintained, which is very similar to the paradigms that have been used in size adaptation studies. Size misperception is commonly reported in studies of size adaptation. It refers to the phenomena that after

adapting to a grating pattern, the bars within a higher spatial frequency grating looked even narrower and those within a lower spatial frequency grating looked even wider (Blakemore and Sutton, 1969; Nishida, Motoyoshi & Tackeuchi, 1999). It is likely that such size adaptation exists in the Gabor paradigm, and this could lead to results that differ from those observed in the typical flash-lag paradigm in which there would be little if any size adaptation. Second, sharpness of the edges is different. There are no sharp edges in Gabor stimuli. The edges are blurred away from the center by decreasing the contrast as a function of a Gaussian curve. However, in the flash-lag effect, the moving objects are usually thin lines or bars with sharp edges. It is possible that blurry edges leave more uncertainty regarding the location of a pattern. This in turn could lead to greater susceptibility to the misperception of size based on the influence of other factors (e.g., motion within the Gabor window). Given the above differences, can motion asymmetry theory also account for the “flash-lag effect”? It is important to test the theory with flash-lag stimuli to determine whether it generalizes across the different experimental contexts.

The current studies were intended to address this issue. In experiments producing the flash-lag effect, a flashed object is perceived to lag behind a moving object, although the two are physically aligned. Is this flash-lag effect also produced by a perceived centroid shift of the moving object, resulting from an asymmetric influence of motion on the leading and trailing edges? If that were the case, then two phenomena should be present as evidence. The first is that a shape distortion of the moving object should be perceived. The perceived shape should be elongated as the leading edge is misperceived to be farther away from its true position than the trailing edge. There is evidence in the literature of this shape distortion. Watanabe and his colleague found such distortion and

showed that the distortion was at a magnitude of $.068^\circ$ (Watanabe, Nijhawan, Khurana, & Shimojo, 2001). However, it could not be determined from the Watanabe et al. experiment which edge is responsible for the shape distortion. Experiment 1 addressed this issue and distinguished the roles of the leading and trailing edges in contributing to the shape distortion of moving objects. It tested whether the leading edge contributed more to the shape distortion than the trailing edge. The other phenomenon is that the leading edge is more influenced by motion than the trailing edge. The shape distortion produced by the leading edge should vary as a function of speed, whereas the distortion produced by the trailing edge should vary less as the speed changes. Experiment 2 tested this hypothesis by using different speeds. Experiment 3 tested whether the magnitude of flash-lag effect can be fully explained by the centroid shift found in Experiments 1 and 2.

In Experiments 1 and 2, the tasks involved “squareness” judgments of moving rectangles. We were interested in how much the perceived shape of an object would change as a result of motion. However, before we could measure shape misperception produced by motion, we wanted to take into account any systematic bias in shape perception. In this case the “horizontal-vertical illusion” (HVI) refers to the misperception of the lengths of horizontal and vertical line segments. It is possible that the HVI could produce a distortion in the perceived shape of a square, so we wanted to measure and correct for such a bias if it existed. A control experiment was conducted to estimate the possible influence of the horizontal-vertical illusion on the perception of “squareness”. A physically perfect square might not be perceived to be perfectly square, because the HVI typically results in the perception of rectangles with longer horizontal edges as squares (McManus, 1978).

Control Experiment: The direction and magnitude of the horizontal-vertical illusion

The control experiment tested the possible existence of the horizontal-vertical illusion in the paradigm that was used in the following experiments. The magnitude and direction of the HVI will be used to control for individual results when measuring the magnitude of shape distortion induced by motion in the following experiments.

Method

Participants.

Six adult observers were tested in this study. They were recruited from the Rice Community. All observers reported normal or corrected-to-normal visual acuity. The author served as one of the observers in this experiment. None of the other observers were aware of the experimental predictions. The same six observers were also tested in the following three experiments.

Apparatus.

The stimuli were displayed on a CRT monitor with a display refresh rate of 75 Hz. Observers were seated 57 cm from this display, with their heads stabilized by chin and forehead rests. Stimulus presentation, timing, and response recording were handled by a PC. The Psychophysics Toolbox for Matlab was used to generate stimuli and record responses.

Stimuli.

In this experiment, a rectangle was presented (See Figure 7). This rectangle was composed of four bars with the same width of 0.17° . The height of the rectangle was 3.84° . The width of the rectangle was varied with 7 levels of horizontal offset around the position at which the rectangle was perfectly square. The offsets were -0.38° , -0.19° ,

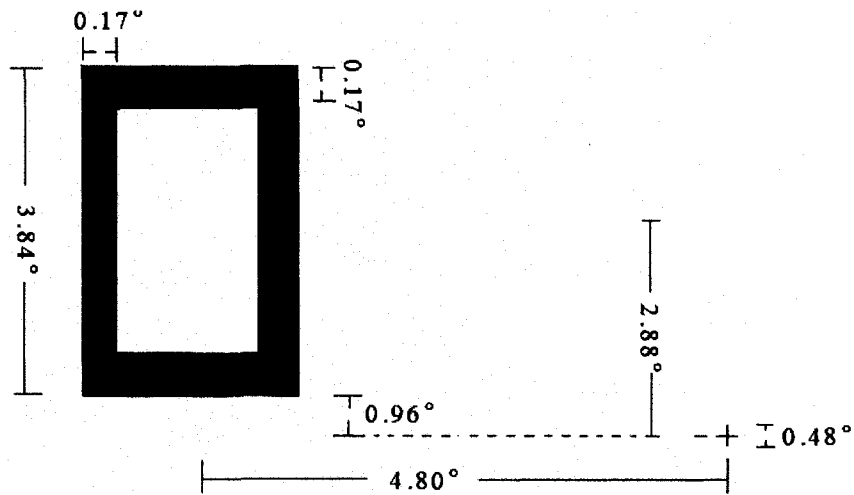


Figure 7. An example of the stimulus used in the control experiment. A stationary rectangle was presented randomly to the left or right of the fixation cross. The vertical extent of the rectangle was constant, whereas the horizontal extent was varied with 7 levels of offset around the point at which the rectangle was physically square.

-0.10°, 0, 0.10°, 0.19°, 0.38°. The negative offset values indicated the rectangle was physically thinner than a square, and the positive values indicated the rectangle was physically fatter than a square. The center of this rectangle was presented 4.80° left or right of the center of fixation and 2.88° above the center of fixation. The fixation was an asterisk shape 0.48° wide and 0.48° tall. The left/right position of the stimulus relative to the fixation point was counterbalanced across trials.

The fixation point was presented at the beginning of and throughout each trial. The fixation was presented with various small offsets to the left or right of the center of the display. The sizes of the offset were the same as those used to vary the width of the rectangles. The position of fixation was randomized between trials. The “jittering” of the location of the fixation point was used to prevent it from serving as a reference point to judge the final positions of the stimulus rectangle’s horizontal edges.

Both the fixation point and stimulus had a luminance of 0.02 cd/m². The background luminance was 8.2 cd/m². Thus, the stimulus looked like a dark outlined rectangle on a bright background.

Procedure.

The rectangle was presented for various durations, then disappeared from the screen. Three presentation durations (long, medium and short durations) were used corresponding to display durations of 0.35s, 0.71s and 1.43s. The three durations were chosen to match the display durations of the slow, medium and fast speed conditions in the following experiments. This allowed the HVI results measured in different duration conditions to be used to interpret the results of the corresponding speed condition in later experiments.

Each duration condition was tested with separate blocks. For each condition, there were a practice session and two data collection sessions. Within each data collection session, there were 112 trials, with 16 trials per offset size. This yielded 32 trials per offset size in each condition. Trials with different offsets were randomized by the computer within a session.

After the rectangle disappeared from the screen, observers were asked to make a two-alternative forced-choice regarding the shape of the rectangle by comparing it to a perfect square. An example of a perfect square was presented at the beginning of each session for 15s as a reference. Two responses could be made: the shape was thinner or fatter than a square. The “thinner” response meant that the horizontal extent of the shape was judged to be less than its vertical extent. The “fatter” response meant that the horizontal extent of the final shape was judged to be greater than its vertical extent. Participants responded “thin” or “fat” by clicking the left or right button on a mouse.

Results

The direction and magnitude of the horizontal-vertical illusion were measured for each observer in each duration condition. It was used as an individual null point of “squareness” perception in later experiments to measure the shape distortion caused by motion information.

For each participant, the percentage of “fatter” response was tabulated for each offset. These percentages and their associated offsets were used to generate a psychometric function (Figure 8). The offset at which the response was 50% was estimated using Probit Analysis and was used to estimate the Point of Subjective Equality

(PSE) (See Figure 9). The PSE estimated the offset at which the shape appeared to be square.

Each participant showed consistent patterns of HVI across duration conditions. In the long duration condition, five of six participants showed an HVI. Observers 1, 3, 5 and 6 overestimated the horizontal extent of the rectangle, and perceived the rectangle as square when it was physically thinner than a square. Their PSE were -0.11° , -0.03° , -0.29° and -0.15° . Observer 2 overestimated the vertical extent of the rectangle and perceived the rectangle as square when it was physically fatter than a square. His PSE was 0.04° . Similarly, in the medium duration condition, five of six participants showed an HVI. Observers 1, 3, 5 and 6 overestimated the horizontal extent of the rectangle, and their PSE were -0.06° , -0.03° , -0.12° and -0.13° . Observer 2 overestimated the vertical extent of the rectangle, and his PSE was 0.04° . In the short duration condition, observers 3, 4, 5 and 6 overestimated the vertical extent of the rectangle, and their PSE were -0.08° , -0.05° , -0.27° and -0.11° . Observer 2 overestimated the vertical extent of the rectangle, and his PSE was 0.05° .

Experiment 1: Difference in the misperception of the leading and trailing edges of an expanding or contracting rectangle

According to motion asymmetry theory, motion has different effects on positional judgments of the leading and trailing edges of a moving object. Specifically, the positional judgment of a leading, moving edge is hypothesized to be more influenced by motion signals than that of a trailing edge. Motion asymmetry theory makes two predictions: one is that the misperception of position of a leading edge is larger than that of a trailing edge; the other is that the magnitude of this edge misperception increases as a

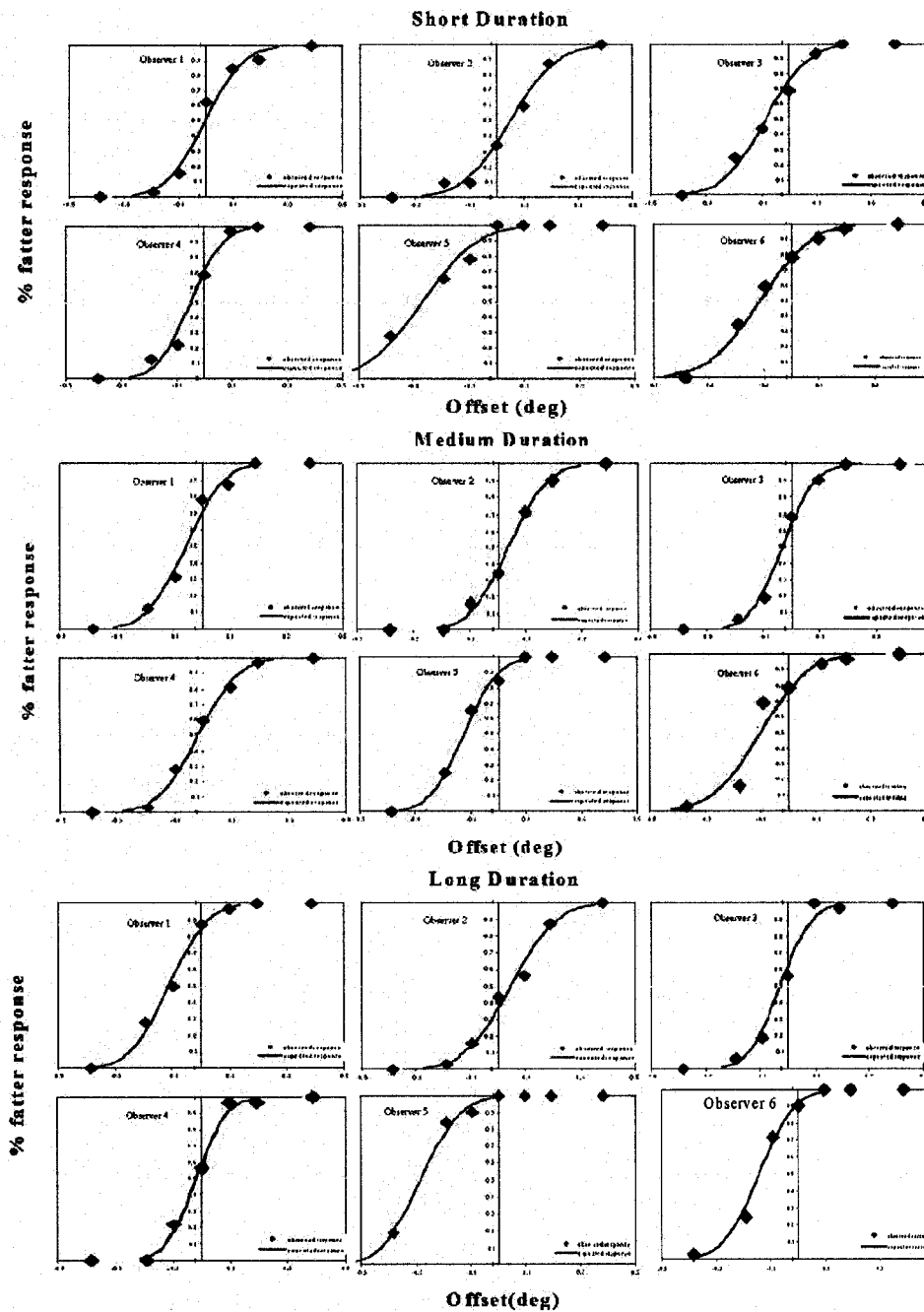


Figure 8. Individual psychometric functions for the percentages of “fatter” response as a function of horizontal offset size across durations. Blue diamond markers represent the observed percentages of “fatter” responses and the red lines represent the best-fitting function using Probit Analysis.

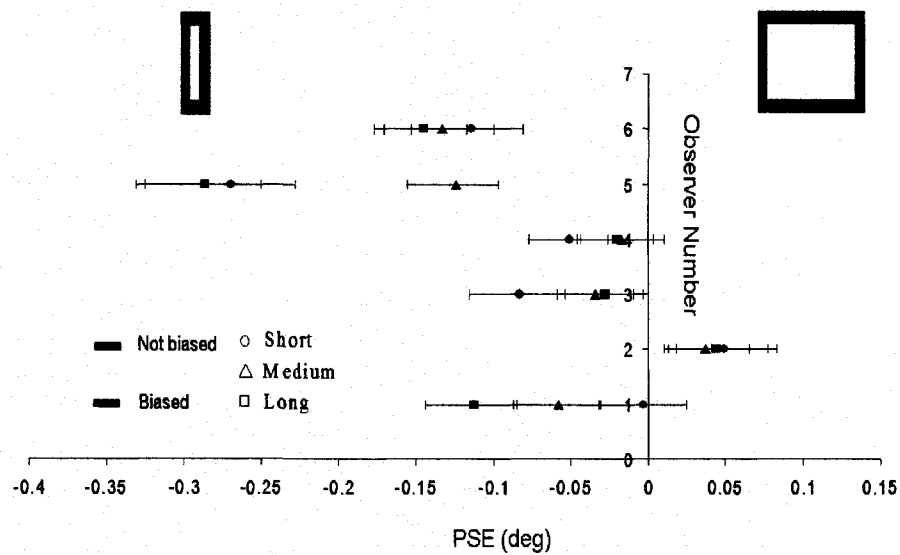


Figure 9. Individual results of the direction and magnitude of the horizontal-vertical illusions estimated by PSEs. Horizontal bars represent 95% confidence intervals. Blue color indicates the existence of HVI and red color coding indicates the absence of HVI. Different marker shapes indicate different duration conditions. The majority of observers showed negative PSEs indicating that they overestimated the horizontal extent of the rectangles and only when the rectangle was physically thinner than a square, was it perceived as square. Only observer 2 consistently showed positive PSEs indicating that he overestimated the vertical extent of the rectangles and only when the rectangle was physically fatter than a square, was it perceived as square.

function of speed, while that of a trailing edge does not or at least that it varies less.

Experiment 1 was conducted to test the first prediction: the position of a leading edge should be misperceived further along its direction of motion than the position of a trailing edge. In this experiment, we presented the motion of the leading and trailing edges separately. This is the potential unique contribution of this experiment. By designing special stimuli, we examined positional misperception of the leading and trailing edges of a moving object separately. In all of the previous studies, these two edges moved together, so it was not possible to attribute any shape distortion uniquely to one or the other edge. The magnitude of shape distortion, as a result of the motion, was measured and compared between the leading and trailing conditions. Since there was only one edge moving in each condition, the shape distortion can be exclusively attributed to the positional misperception of the moving edge in that condition. According to motion asymmetry theory, in Experiment 1, we should find a larger shape distortion in the leading edge condition than in the trailing edge condition.

Method

Apparatus & Stimuli.

The same apparatus was used as the control experiment. In this experiment, only the leading or trailing edge of an object moved in each condition. In the leading edge condition, a thin rectangle was presented at first (See Figure 10). This rectangle was composed of four bars with the same width of 0.17° same as the control experiment. The rectangle was 3.84° tall and 0.50° wide. The center of this rectangle was presented 6.47° left or right of the center of fixation and 2.88° above the center of fixation. When the rectangle appeared, the vertical edge that was closer to the fixation moved horizontally at

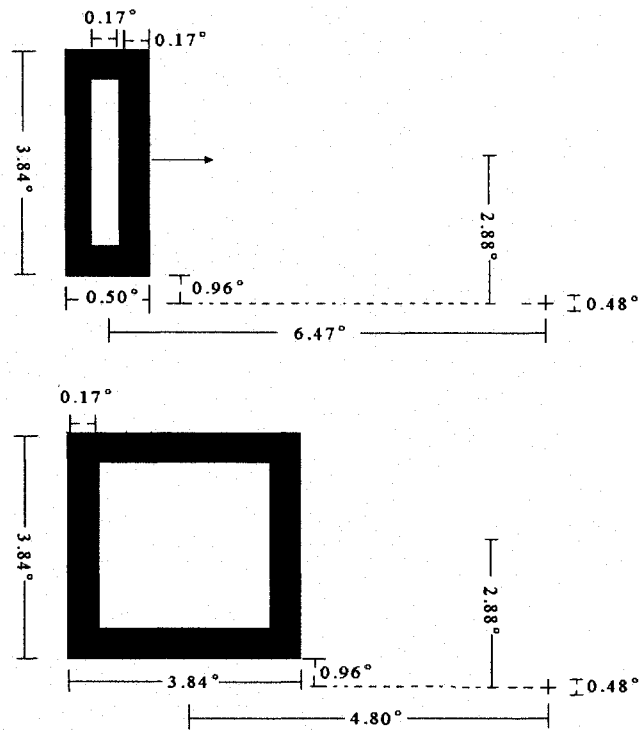


Figure 10. An example of the leading edge condition in Experiment 1. A thin rectangle was first presented randomly to the left or right of the fixation cross. In this example the rectangle was presented on the left. Then the edge that was closer to the fixation point moved toward the fixation point at a speed of 4.7 °/s. The edge moved for 0.71s, then stopped and disappeared from the screen. The rectangle gradually grew fatter as a result of the movement of the leading edge.

a speed of $4.7^\circ/\text{sec}$ toward the direction of fixation. As a result of the edge movement, the rectangle gradually *grew* into an approximate square. In this condition, the edge that moved was the leading edge of the object, and there was no motion of the “trailing” edge.

In the trailing edge condition, similarly, a fat rectangle was present (See Figure 11). The rectangle was composed of the same bars with a width of 0.17° as in the previous condition. It was the same height of 3.84° . The width of this rectangle was much wider at 7.18° . The center of this rectangle was presented 6.47° left or right of the center of the fixation and 2.88° above the fixation. The vertical edge that was further away from the fixation center moved horizontally at $4.7^\circ/\text{sec}$ toward the center. The rectangle gradually *shrank* into an approximate square. The edge that moved was the trailing edge of this object, and there was no motion of the “leading” edge.

One thing that should be mentioned is that an edge is usually defined in the literature by a spatial change in luminance. In our stimuli the “edges” that moved had width. So technically the first bright-dark transition should be labeled as the leading edge and the second dark-bright transition should be labeled as the trailing edge (Figure 12). Therefore, technically there were both leading and trailing edges moving in each condition. In our experiment, however, we only considered the outer edges of the shapes. It was the position of those edges that defined the perceived shape of the rectangle. Therefore, the bright-dark transition in the leading edge condition was the leading edge of the rectangle, and the dark-bright transition in the trailing condition was the trailing edge (See Figure 13 for our definition of leading and trailing edges).

In both conditions, the edges stopped moving at various offsets around the position at which the shape of the rectangle was perfectly square. There were 7 levels of

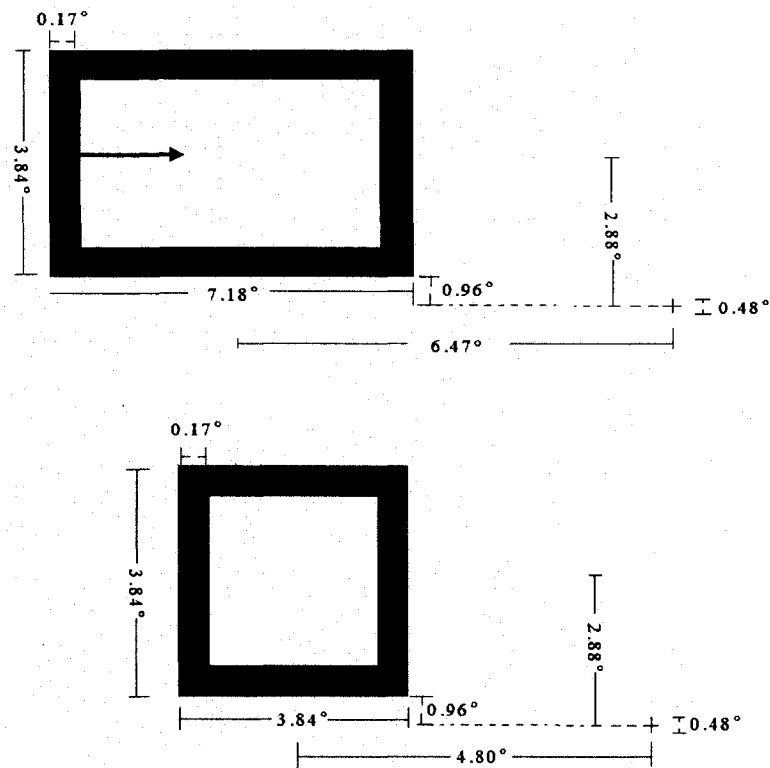


Figure 11. An example of the trailing edge condition in Experiment 1. The trailing edge condition was very similar to the leading edge condition, except that it involved trailing edge motion. A fat rectangle was first presented randomly to the left or right of the fixation cross. In this example the rectangle was presented on the left. Then the edge that was farther away from the fixation point moved toward the fixation point at a speed of 4.7 degree/second. The rectangle gradually shrank into a square as a result of the trailing edge motion.

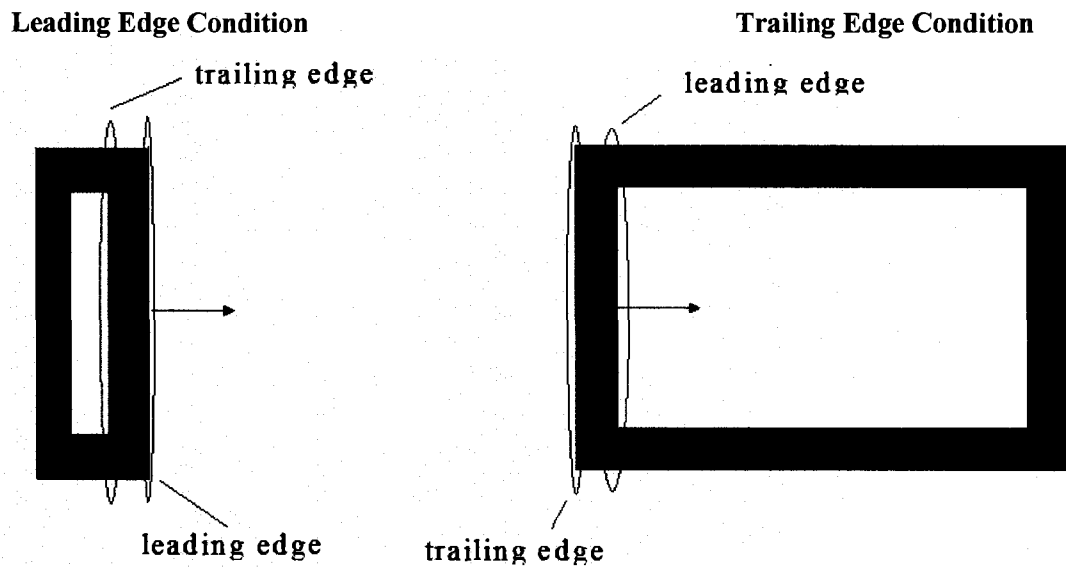


Figure 12. Illustration of stimulus edges defined by the spatial change in luminance. The “edges” that moved had width. Therefore, technically the first bright-dark transition should be labeled as the leading edge and the second dark-bright transition should be labeled as the trailing edge in each condition.

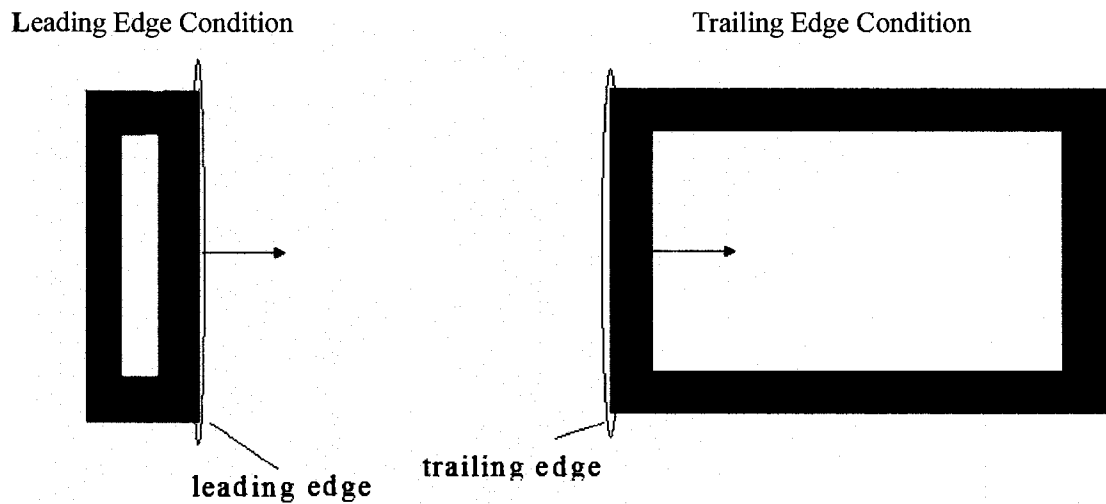


Figure 13. Illustration of edges defined in the current experiments. Only the outer edges of the shapes were considered and defined as leading and trailing edges. Therefore, the bright-dark transition in the leading edge condition was the leading edge of the rectangle, and the dark-bright transition in the trailing was the trailing edge.

offset, and the sizes of offset were the same as the previous experiment. As soon as the edge stopped moving, the object disappeared. The shape of the object was judged after the object disappeared. It is important to note that the absolute positions of the final figures relative to fixation in both conditions were identical. The reason for this will be explained in the method section of Experiment 3. The traveling time of the edge was the same in both conditions given the same offset size.

The starting positions and directions of motion relative to the fixation point were counterbalanced within each condition. The fixation point was presented at the beginning and throughout each trial. The fixation was jittered as it was in the control experiment and the reason for “jittering” the location of the fixation point was to prevent it from being a cue to judge the final position of the moving edge.

Procedure.

In each condition, there were a practice session and two data collection sessions. A total 32 trials per offset size were collected in each condition. Trials with different offsets were randomized by the computer. Participants finished all three sessions (one practice and two data collection) of the same condition (leading-edge or trailing-edge) first, before moving to the other condition. The sequence of conditions was counterbalanced across participants. Between sessions, observers were allowed to take a break.

Observers made a two-alternative forced-choice regarding the final shape of the rectangle by comparing it to a perfect square. An example of a perfect square was presented in the beginning of each session for 15 s as a reference. Two responses could

be made: the shape was thinner or fatter than a square. Participants responded “thin” or “fat” by clicking the left or right button on a mouse.

Results

Motion asymmetry theory predicted that the perceived shape of the object should change with the type of motion. The shape of the object should be elongated to a greater extent in the leading edge condition than in the trailing edge condition. This would show that the perceived locations of edges are ahead of their physical positions along their directions of motion and that the leading edge is mislocalized to a greater extent compared to that of the trailing edge.

The percentage of “fatter” responses was calculated for each offset. The offset at which the response is 50% was estimated using Probit Analysis based on the observed percentages and their associated offsets. Those offsets were used to estimate the Point of Subjective Equality (PSE). The PSE estimated the offset at which the final shape appeared to be square. The individual estimates of the magnitude of shape misperception produced by motion were calculated using the HVI results from the medium duration condition in the control experiment and the PSE measured in this experiment. For those observers who showed evidence of an HVI, the misperception of shape in the current experiment was corrected using the formula $PSE_{\text{Motion Effect}} = PSE_{\text{observed}} - PSE_{\text{HVI}}$ in both the leading and trailing edge conditions. In the absence of any motion influence on shape perception, the PSE should be equal to PSE_{HVI} indicating any distortion was a result of an HVI. Motion asymmetry theory predicts that the $PSE_{\text{Motion Effect}}$ should be negative in the leading edge condition, which would indicate that the leading edge was misperceived in the direction of motion (ahead of when it actually was). Conversely, the $PSE_{\text{Motion Effect}}$

should be positive or zero in the trailing edge condition, which would indicate that the trailing edge was either misperceived in the direction of motion or correctly perceived. The size of the misperception is the absolute value of $PSE_{\text{Motion Effect}}$. Motion asymmetry theory also predicts that the absolute value of the $PSE_{\text{Motion Effect}}$ should be greater in the leading edge condition than in the trailing edge condition, indicating that the misperception of the position of the leading edge should be greater than that of the trailing edge.

$PSE_{\text{Motion Effect}}$ estimates for each observer in both the leading and trailing edge conditions are shown in Figure 14. Observers 1 and 4 misperceived the leading edge in the direction of motion, and the estimates of their shape distortions were 0.22° and 0.19° , respectively. Observers 3 and 5 misperceived the leading edge in the direction opposite to that of the motion, and the estimates of their shape distortions were 0.16° and 0.11° , respectively. Observers 2 and 6 did not show any significant misperception of the position of the leading edge. For the trailing edge, observers 1, 3, 4 & 5 showed misperception in the direction of motion, and the estimates of their shape distortions were 0.11° , 0.09° , 0.13° and 0.13° . Observer 2 misperceived the trailing edge in the direction opposite to that of the motion, and the estimates of his shape distortion was 0.10° . Observer 6 did not show misperception of the trailing edge.

The group mean of the shape distortion for the leading edge was -0.01° , and that of the trailing edge was 0.07° . Statistically, neither of these was different from 0.

Experiment 2: Misperception of the leading and trailing edges as a function of speed
 Experiment 2 was intended to test the second prediction from motion asymmetry theory

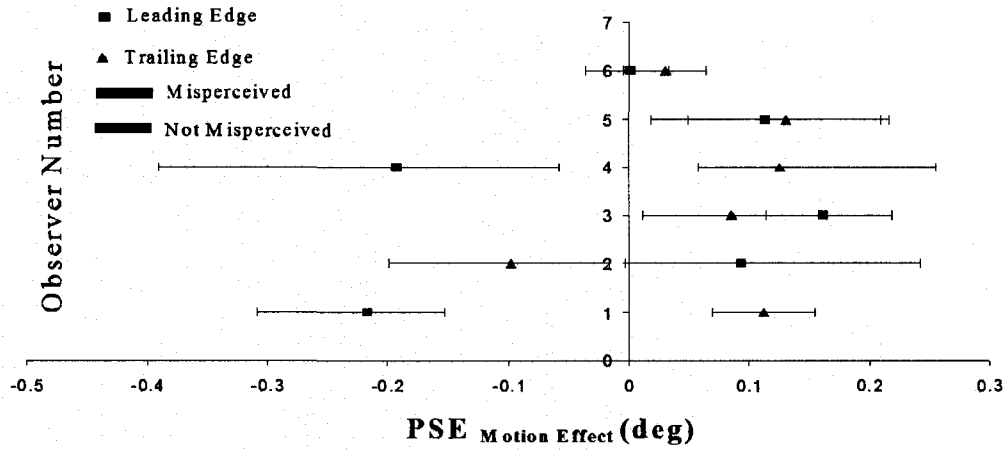


Figure 14. Misperception of the leading and trailing edges. Square markers represent the $PSE_{\text{Motion Effect}}$ of the leading edge and triangle markers represent those of the trailing edge. Blue colored markers indicate that the misperception is reliably different from zero and red colored markers indicate that the misperception is not reliably different from zero. The horizontal bars represent the range of the 95% confidence intervals. Two of six observers misperceived the leading edge in the direction of motion and two misperceived the leading edge in the direction opposite to that of the motion. Four of six observers misperceived the trailing edge in the direction of motion.

that the magnitude of the misperception of a leading edge increased as a function of speed; whereas that of a trailing edge did not or varied less. In this experiment, the leading and trailing edges moved at two speeds, which were either slower or faster than the one used in Experiment 1. The shape distortion was measured at these two speeds. Combining the results from Experiments 1 and 2, the shape distortion produced by motion was compared at three speeds (low, medium and high) between the leading and trailing edge conditions. Motion asymmetry theory predicted that the misperception produced by motion should increase as the speed increased in the leading edge condition, and that it should increase less or none at all in the trailing condition.

Method

Stimuli & Procedure.

The same apparatus and stimuli for both the leading and trailing edge conditions were used here as were used in Experiment 1. In this experiment, the edges moved at two speeds: 2.4°/s and 9.4°/s (low and high). The shape of the object was judged when the edge stopped moving and disappeared from the screen. Observers made a two-alternative forced-choice regarding the final shape of the rectangle. Two responses can be made: the shape is thinner or fatter than a square. Participants responded “thin” or “fat” by clicking the corresponding “left” or “right” button.

Each speed was tested within separate blocks. Each block included six sessions, three sessions (one practice session and two data collection sessions) with each of the edge conditions. The sequence of blocks with different speeds was counterbalanced across subjects. In each block, there were 32 trials per offset size in each condition. Trials

with different offsets were randomized by the computer. Between blocks, observers took a break.

Results

For each observer, the percentage of “fatter” response was tabulated for both the leading and trailing edges in the low and fast speed conditions. PSE_{observed} was estimated using Probit Analysis based on the observed percentages and their associated offsets. The PSE_{HVI} measured in the control experiment for each observer was used to correct the estimate of shape distortion produced by motion ($PSE_{\text{Motion Effect}}$) using the formula: $PSE_{\text{Motion Effect}} = PSE_{\text{observed}} - PSE_{\text{HVI}}$. Specifically, the PSE_{HVI} measured at the long duration in the control experiment was used to estimate the $PSE_{\text{Motion Effect}}$ in the slow speed condition, and the PSE_{HVI} measured at the short duration was used to calculate the $PSE_{\text{Motion Effect}}$ in the fast speed condition, because the display times of the stimuli were identical between the conditions in the control and the current experiments.

The results for individual observers in both the low and high speed conditions are shown in Figure 15a and 15b. In the low speed condition, observers 1 and 2 misperceived the leading edge in the direction of motion, and their $PSE_{\text{Motion Effect}}$ were -0.17° and -0.1° . Observers 4 and 5 misperceived the leading edge in the direction opposite to that of the motion, and their $PSE_{\text{Motion Effect}}$ were 0.06° and 0.21° . Observers 3 and 6 showed no significant misperception of the position of the leading edge. In the trailing edge condition, observers 1, 3, 5 and 6 misperceived the edge in the direction of motion, and their $PSE_{\text{Motion Effect}}$ were 0.22° , 0.22° , 0.30° and 0.27° . Observers 2 and 4 did not misperceive the position of the trailing edge. In the fast speed condition, observer 1 misperceived the leading edge in the direction of motion, and his $PSE_{\text{Motion Effect}}$ was

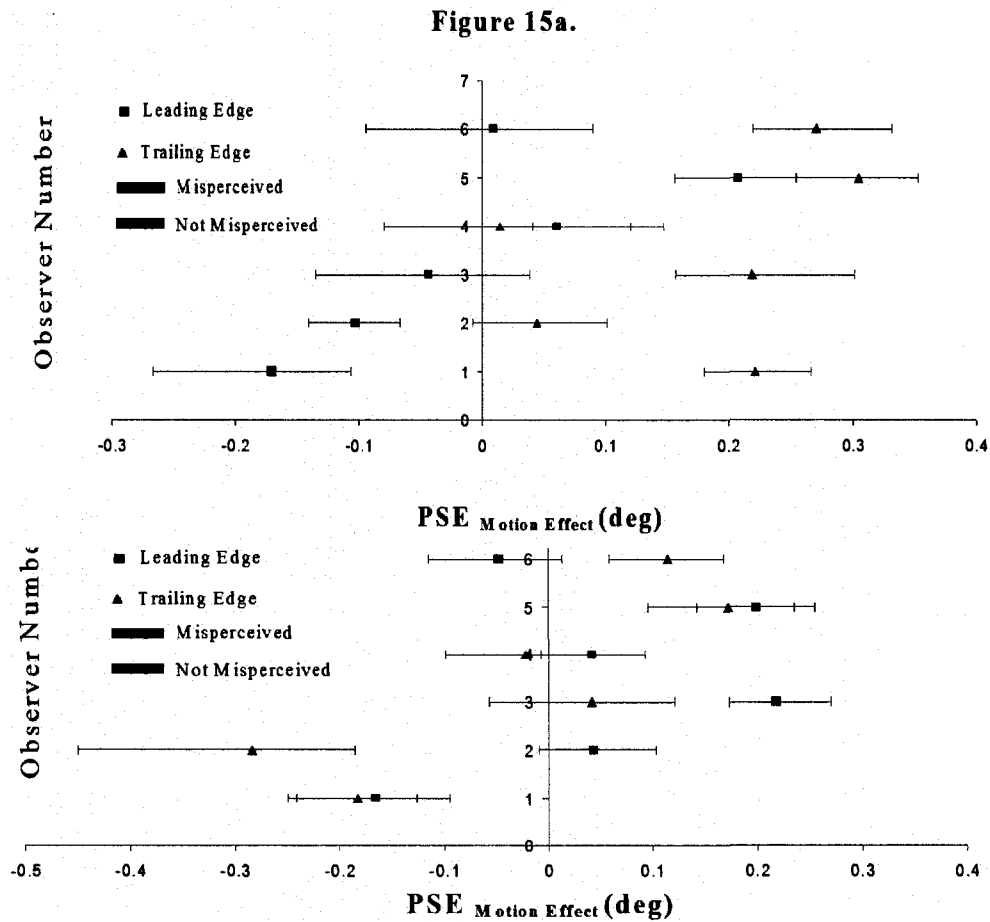


Figure 15. Individual results for the misperception of the leading and trailing edges in low and fast speed conditions. Figure 15a. shows the results of the low speed condition. In the leading edge condition, two observers misperceived the edge in the direction of motion, whereas two observers misperceived it in the direction opposite to that of the motion. In the trailing edge condition, four observers misperceived the edge in the direction of motion. Figure 15b. shows the results of the fast speed condition. In the leading edge condition, only one observer misperceived the edge in the direction of motion, whereas two observers misperceived it in the direction opposite to that of the motion. In the trailing edge condition, two observers misperceived the edge in the direction of motion, whereas two observers misperceived it in the direction opposite to that of the motion.

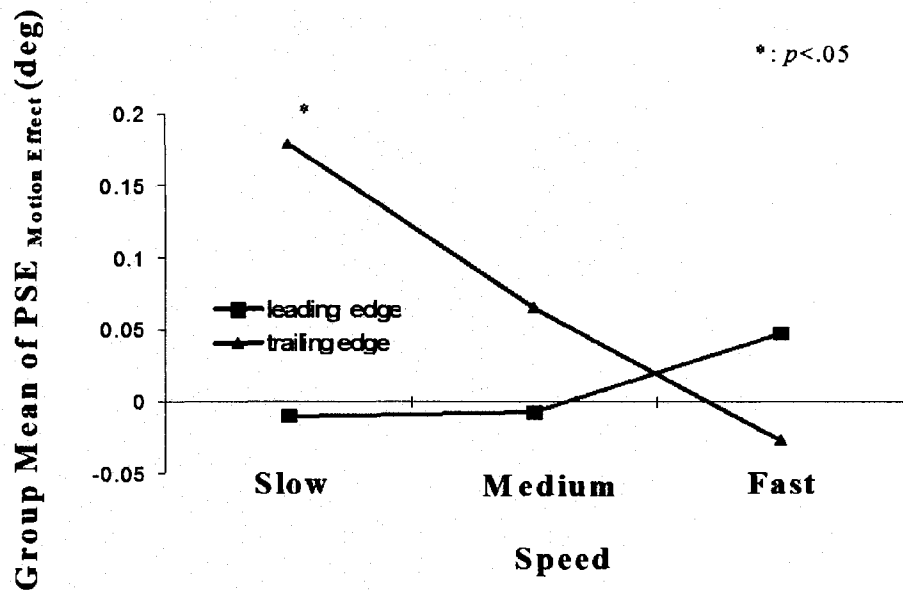


Figure 16. Group results for the misperception of the leading and trailing edges as a function of speed. Statistically, only the misperception of the trailing in low speed condition was different from 0.

-0.17°. Observers 3 and 5 misperceived the leading edge in the direction opposite to that of the motion, and their $PSE_{\text{Motion Effect}}$ were 0.22 and 0.20°. Observers 2, 4 and 6 did not misperceive the position of the leading edge. For the trailing edge, observers 5 and 6 misperceived it in the direction of motion, and their $PSE_{\text{Motion Effect}}$ were 0.17° and 0.11°. Observers 1 and 2 misperceived the trailing edge in the direction opposite to that of the motion and their $PSEs_{\text{Motion Effect}}$ were -0.18° and -0.28°. Observers 3 and 4 did not misperceive the position of the trailing edge.

Combined with the results of the previous experiment (See Figure 16), the group data suggested that the leading edge was misperceived in the direction of motion in both the low and medium speed conditions with the same magnitude of 0.01°, and it was misperceived 0.05° in the direction opposite to that of the motion in the fast speed condition, although it should be noted that the group means for these conditions did not differ significantly from zero. The trailing edge was misperceived 0.18° and 0.07° in the direction of motion in slow and medium conditions respectively, and it was misperceived 0.03° in the direction opposite to that of the motion in the fast condition. Only the misperception of the trailing edge in the low speed condition was statistically different from zero, $t(5)=3.63, p<.05$. We also found through an ANOVA that there was an interaction between speed and edge condition, $F(2, 10) = 4.17, p<.05$. This suggested that the effect of speed was different on the misperception of the leading and trailing edges. We analyzed simple main effects to further explain the interaction. We found that speed did not have an effect on the misperception of the leading edge, but it influenced the misperception of the trailing edge, $F(2, 10) = 7.15, p<.05$. The misperception of the

trailing edge in the direction of motion decreased linearly as the speed increased, $F(1, 5)=13.8, p<0.5$.

This interaction reveals that our results were opposite in all respects to the predictions of motion asymmetry theory. First, the magnitude of shape distortion was greater for the trailing edge instead of for the leading edge. Second, as speed increased, the magnitude of shape distortion decreased rather than increased as predicted by motion asymmetry theory.

Experiment 3: Predicting the flash-lag illusion from the centroid shift estimated from Experiments 1 and 2

In the previous experiments, we found that the moving edges were misperceived in the direction of motion. It was primarily the trailing edge that was misperceived. Although this was not what motion asymmetry theory predicted, this misperception could also produce a centroid shift in the direction of motion (See Figure 17). If it is the centroid shift that gives rise to a flash-lag illusion, then the size of the centroid shift should be equal to the magnitude of the flash-lag illusion.

In Experiment 3, we measured the flash-lag illusion. This time we had the whole object moving, instead of its individual edges. The object was the same square used in previous experiments and the square moved at three speeds, also the same as in the previous experiments. An identical square was flashed below the moving square after it had traveled for some time. The magnitude of the flash-lag effect was measured by estimating the position of the moving square at which it appeared to be aligned with the flashed square.

Method

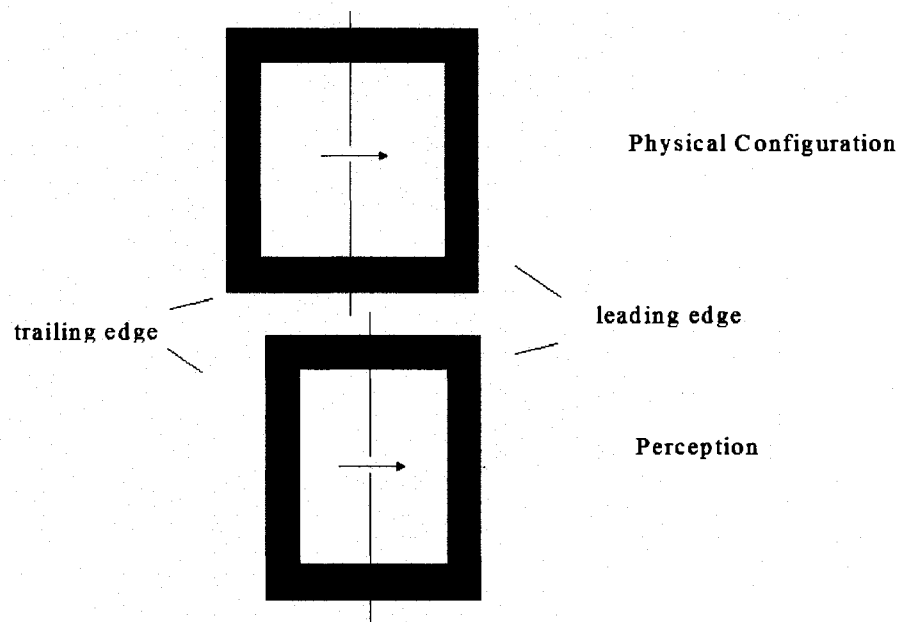


Figure 17. Illustration of estimating the centroid shift of a moving object based on the results of the previous experiments. The centroid shift should be in the direction of motion because the trailing edge was misperceived ahead of its physical location, whereas the leading edge was not misperceived.

Apparatus & Stimuli.

The same apparatus was used as the previous experiments. In this experiment, a moving square (See Figure 18) was presented. The center of the square was 8.15° left or right to and 2.88° above the fixation point. The square size was $3.84^\circ \times 3.84^\circ$. This is the same size as the perfect square that appeared at the end of some of the trials in Experiments 1 and 2. It started traveling toward the fixation as soon as it appeared on the display. The square traveled at three speeds: low, medium and high ($2.4^\circ/\text{s}$, $4.7^\circ/\text{s}$ and $9.4^\circ/\text{s}$). The speeds used here were also the same as previous experiments. This allowed a comparison of the magnitude of the flash-lag effect from Experiment 3 and the size of the positional shift from Experiment 1 and 2 at all three speed conditions. After the square traveled for some time, the center of the square was 4.80° left or right of the fixation point. At that point, an identical square was flashed 5.76° (center to center distance) below the moving square for 13 ms (1 frame)(See Figure 19). The traveling square stopped moving at the time when the flash appeared and disappeared with it. The square was flashed with 7 horizontal offsets relative to the position of the moving square. The offsets were -0.1° , 0° , 0.1° , 0.19° , 0.38° , 0.77° and 1.54° . Negative offset values mean the square was flashed behind the moving square, and vice versa for positive values.

The final position of the moving square when it disappeared was selected to be the same as that in Experiments 1 and 2. The presentation of both of the initial and final positions of the moving square in this experiment ensured that the leading and trailing edges of this square moved precisely the same way as they did when they were presented independently in Experiments 1 and 2 (See Figure 20).

Procedure.

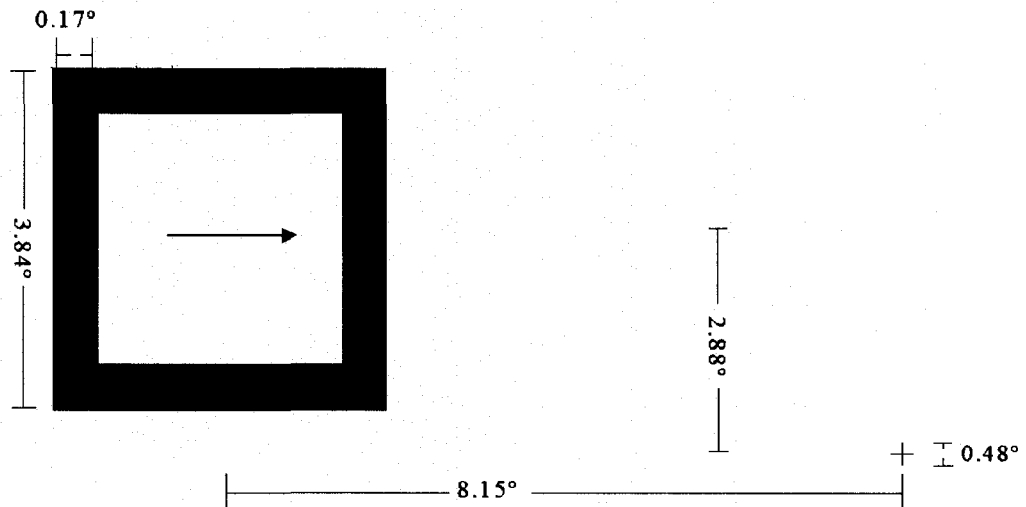


Figure 18. Illustration of the moving square used in Experiment 3. The square was presented on the left or right of the fixation point, and then moved toward it. In this example, the square was presented to the left of the fixation and moved to the right. The arrow indicates the moving direction.

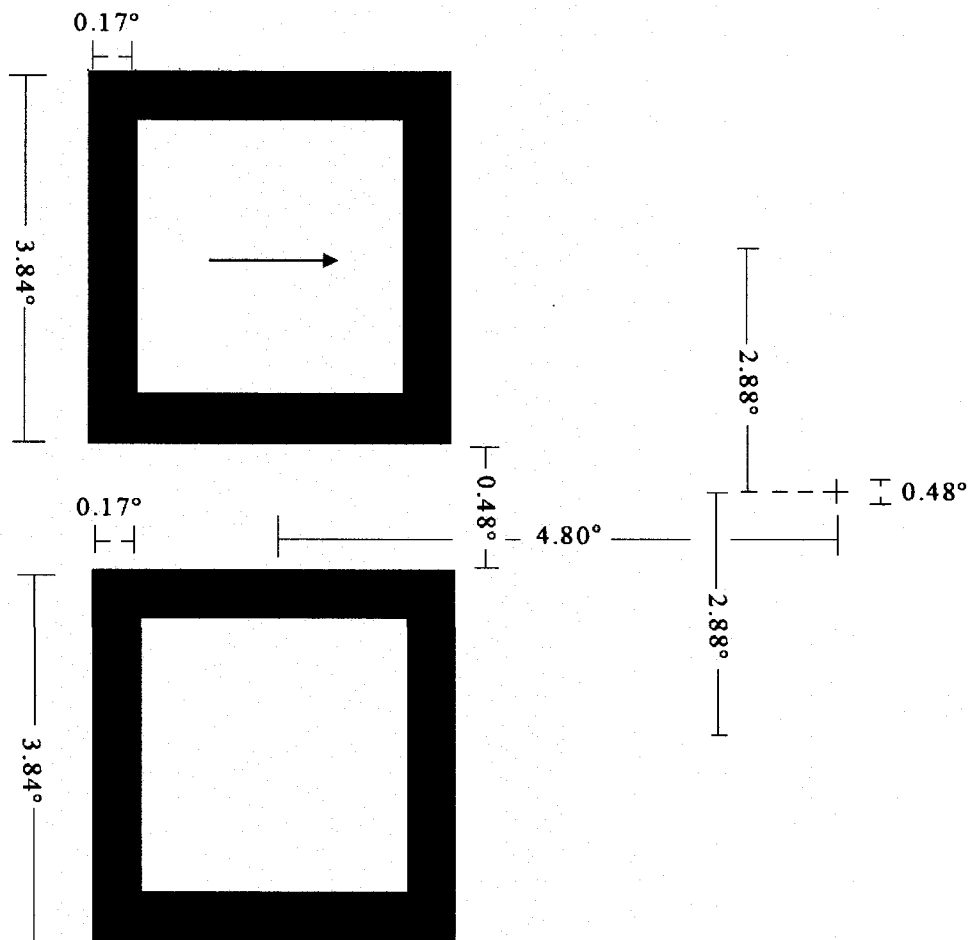


Figure 19. Illustration of the flashed and moving squares used in Experiment 3. The top square is the moving square. When it moved to the position which was 4.80° away from the fixation, an identical square was flashed below it. The square was flashed at one of 7 positions horizontally offset relative to the center of the moving square. Both the moving and flashed squares disappeared from the screen, after the square flashed for 13 ms. Participants were required to judge the horizontal position of the flashed square relative to the moving square.

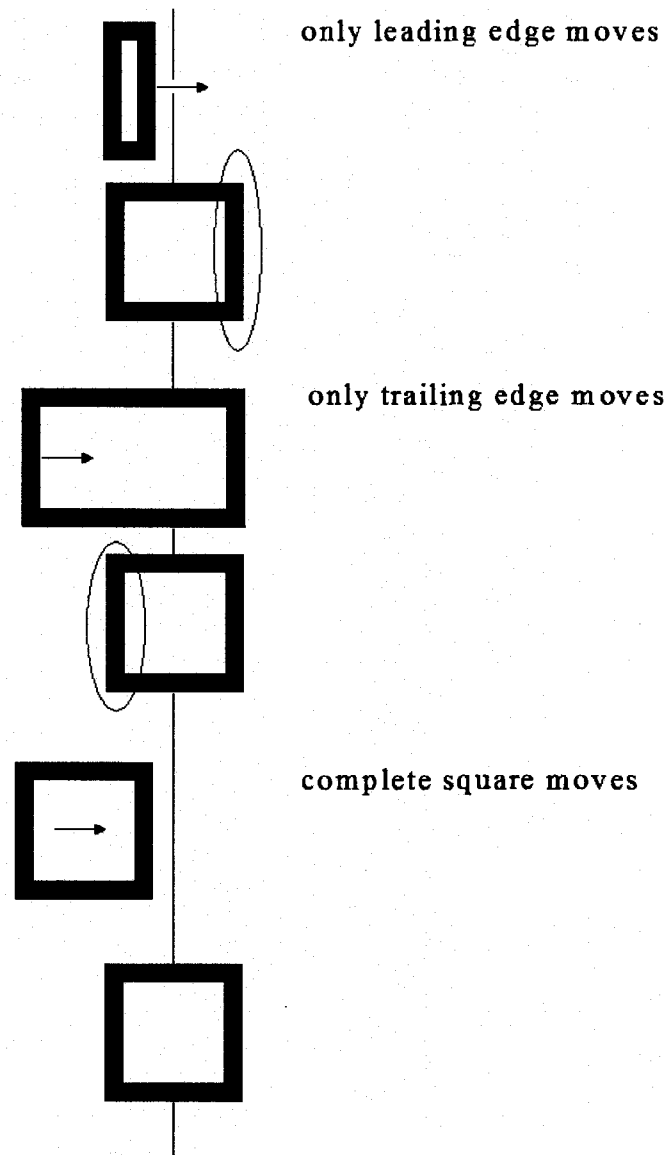


Figure 20. An illustration of the initial and final positions of the moving square in all three experiments. The centers of the final positions of the stimulus are always the same. The movements of the leading and trailing edges in Experiments 1 and 2 are precisely the same as they move in Experiment 3.

Each speed was tested within separate blocks. Each block included three sessions (one practice session and two data collection sessions). The sequence of blocks with different speeds was counterbalanced across subjects. In each block, there were 32 trials per offset size. Trials with different offsets were randomized by the computer. Between blocks, observers took a break.

Observers made a two-alternative forced-choice regarding the alignment of the moving and flashed squares. Two responses can be made: the flashed square is perceived to the left or right of the moving square. Participants responded “left” or “right” by clicking the corresponding mouse button.

Results

We measured the magnitude of the flash-lag illusion across speeds. For each observer, the percentage of trials on which s/he perceived the flashed square as leading the moving square was tabulated for each offset in each speed condition. The $PSE_{\text{Flash-lag Illusion}}$ is the offset at which the response was 50%, and this was used as the measure of the magnitude of the flash-lag illusion.

The $PSE_{\text{Flash-lag Illusion}}$ was estimated in each speed condition using Probit Analysis. The flash-lag illusion should be evidenced by finding positive values for the $PSE_{\text{Flash-lag Illusion}}$, which would indicate that only when the square was flashed ahead of the moving square, would the two squares be perceived as aligned.

The results for individual observer in all three speed conditions are shown in Figure 21. In the low speed condition, four of six observers showed the flash-lag illusion. They were observers 1, 2, 3 and 6, and their $PSE_{\text{Flash-lag Illusion}}$ were 0.29° , 0.44° , 0.87° and 0.22° . In the medium speed condition, three observers showed the flash-lag illusion.

Figure 21a

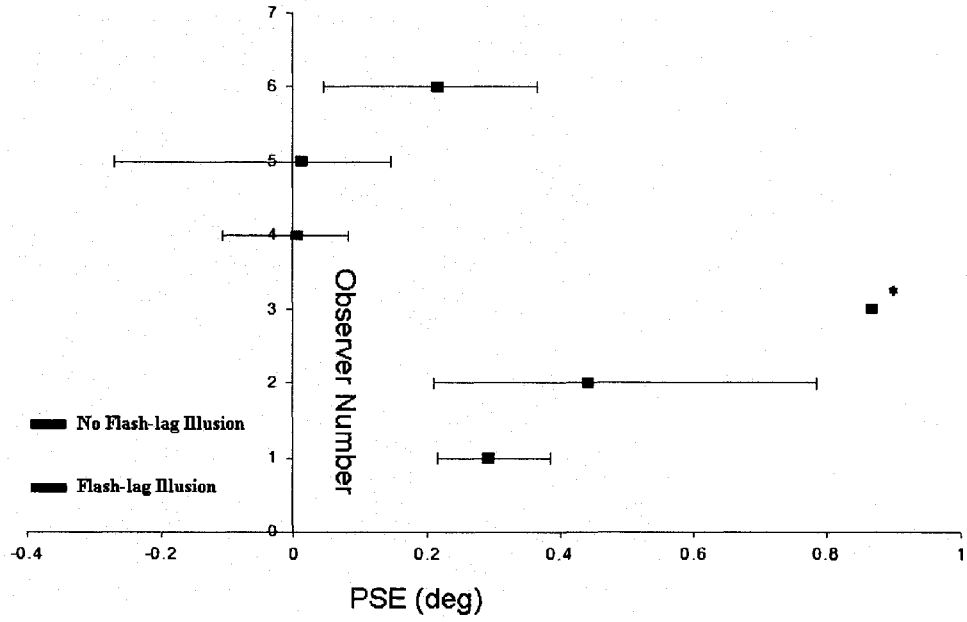
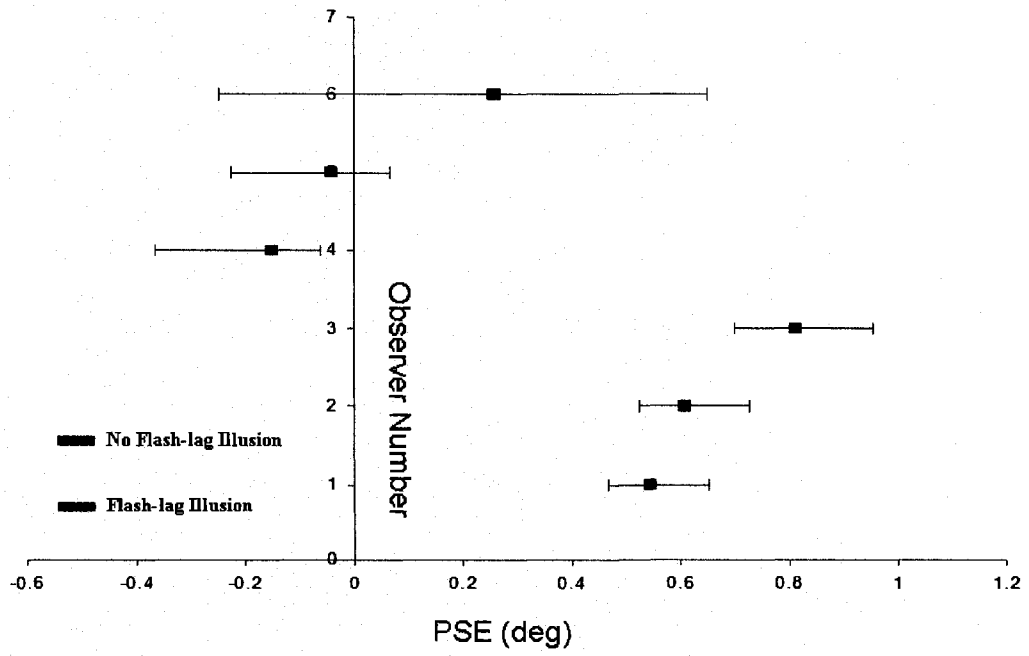


Figure 21b



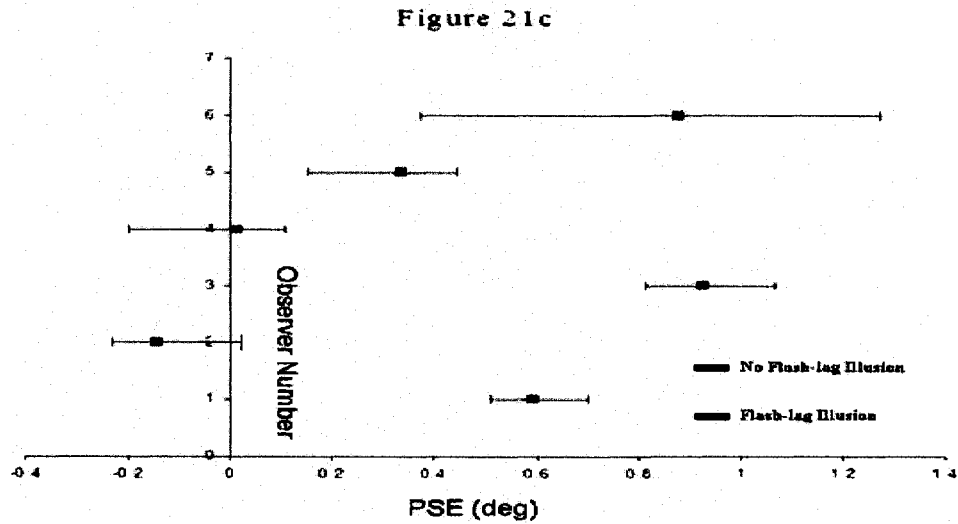


Figure 21. Individual results of PSE across speed conditions. Horizontal bars represent 95% confidence intervals. Figure 21a. shows results from the slow speed condition, four of six observers showed a flash-lag illusion. The asterisk indicates the confidence intervals for observer 3 can not be calculated. Figure 21b. shows results from the medium speed condition, three of six observers showed a flash-lag illusion. Figure 21c. shows results from the fast speed condition, four of six observers showed a flash-lag illusion.

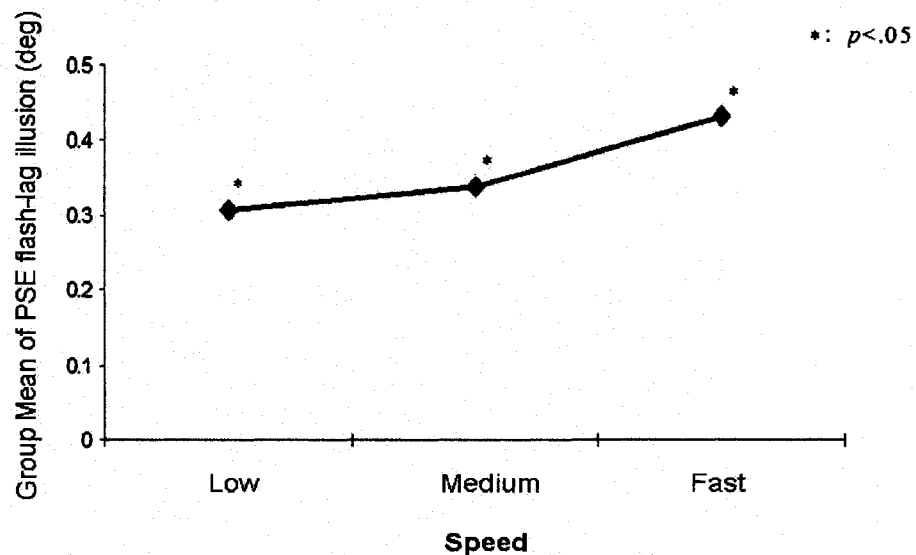


Figure 22. Group means of $PSE_{\text{Flash-lag Illusion}}$ varying as a function of speed. Positive values provide evidence of the flash-lag illusion. All the values were statistically different from 0.

They were observers 1, 2 and 3, and their $PSE_{\text{Flash-lag Illusion}}$ were 0.55° , 0.61° and 0.81° . In the fast speed condition, four observers showed the flash-lag illusion, and their $PSE_{\text{Flash-lag Illusion}}$ were 0.59° , 0.92° , 0.34° and 0.88° .

On the group level, the group means of the $PSE_{\text{Flash-lag Illusion}}$ were 0.31° , 0.34° and 0.43° in the low, medium and high speed conditions (See Figure 22), respectively. According to a one-tailed t-test, all the $PSE_{\text{Flash-lag Illusion}}$ were significantly different from zero [low speed condition, $t(5)=2.33$, $p<.05$; medium speed condition, $t(5)=2.17$, $p<.05$; high speed condition, $t(5)=2.39$, $p<0.05$].

The second analysis step was to estimate the size of the centroid shift based on the data from Experiments 1 and 2 (and from the control experiment). Misperception magnitudes were measured separately for the leading and trailing edges. The centroid shift can be calculated using the formula: $(PSE_{\text{Trailing}} - PSE_{\text{Leading}})/2$. At each speed, the size of centroid shift was calculated based on the individual results. On the individual level, five of six observers showed a centroid shift in the direction of motion, and the magnitudes were 0.20° , 0.07° , 0.13° , 0.05° and 0.13° in the low speed condition. Only one observer showed a centroid shift in the direction opposite to that of the motion, and the magnitude was 0.02° . In the medium speed condition, four of six observers showed a centroid shift in the direction of motion and the magnitudes were 0.16° , 0.16° , 0.01° and 0.02° . Two observers showed a centroid shift in the direction opposite to that of the motion, and the magnitudes were 0.10° and 0.04° . In the high speed condition, five observers showed a centroid shift in the direction opposite to that of the motion, and the magnitudes were 0.02° , 0.32° , 0.18° , 0.06° and 0.03° . Only one observer showed a centroid shift in the direction of motion, and the magnitude was 0.16° .

Figure 23a

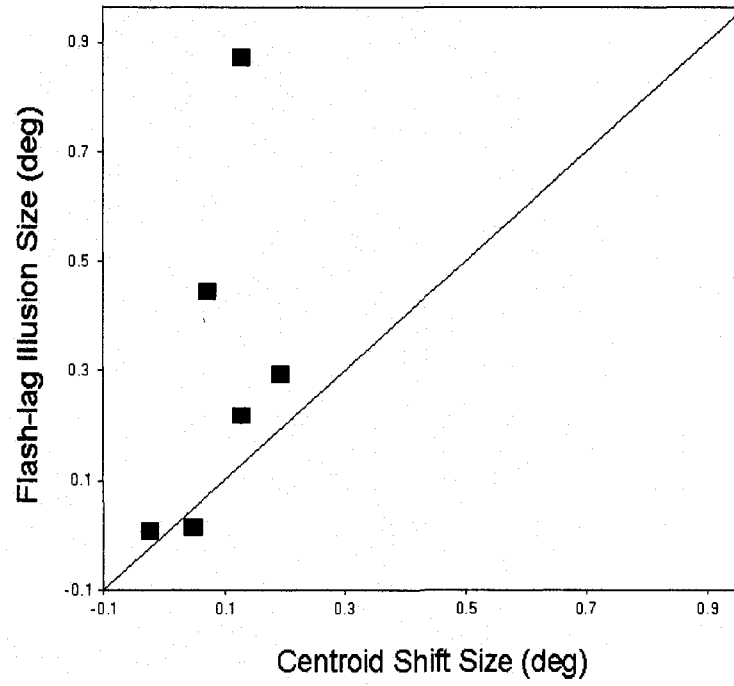
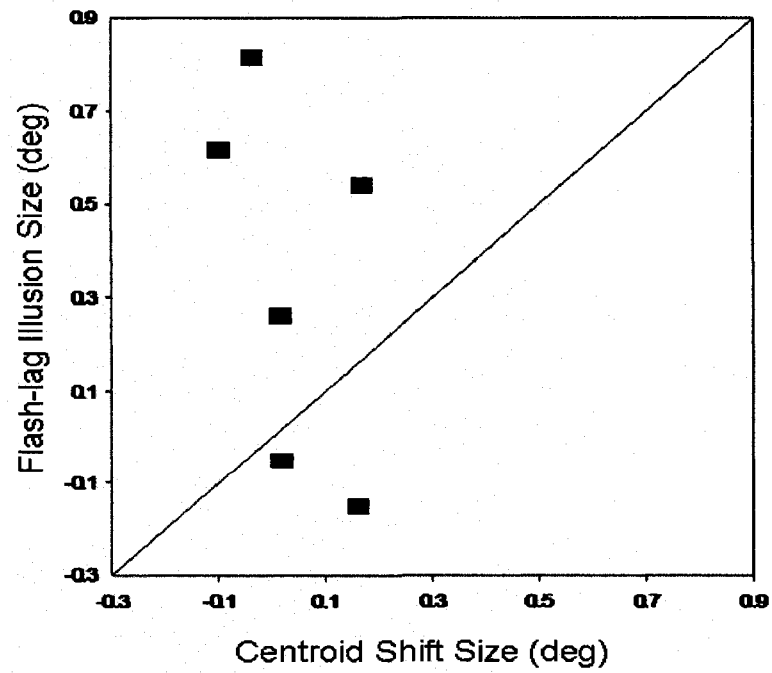


Figure 23b



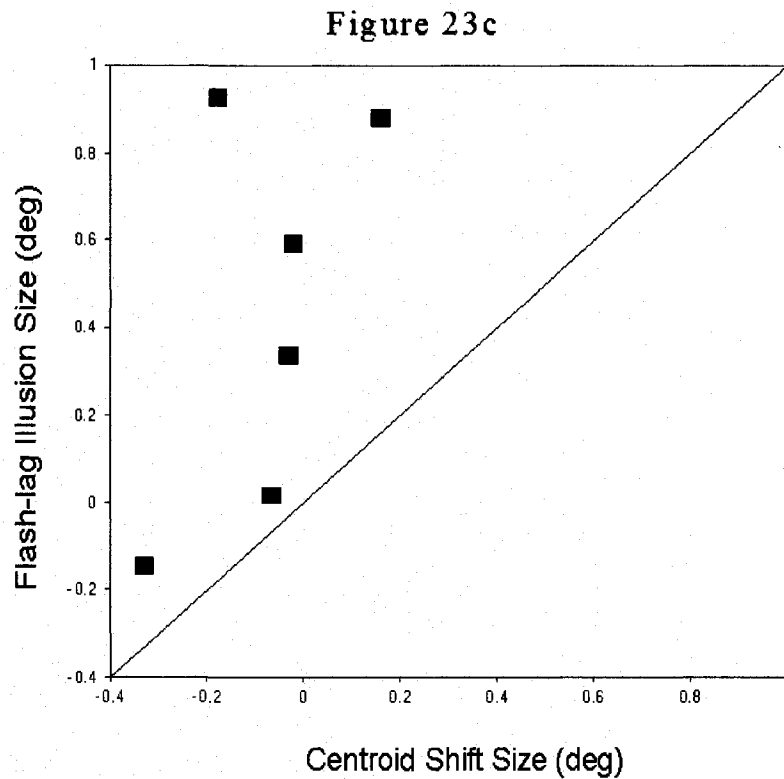


Figure 23. Individual results of the flash-lag illusion size plotted against the calculated centroid shift size for each subject. If the centroid shift perfectly predicted the flash-lag illusion, then all the data should fall on the diagonal line. Figure 23a. shows the results from the slow speed condition. The centroid shift underestimated the flash-lag illusion for five of six observers. Figure 23b. shows the results from the medium speed condition. The centroid shift underestimated the flash-lag illusion for four of six observers. Figure 23c. shows the results from the high speed condition. The centroid shift underestimated the flash-lag illusion for all six observers.

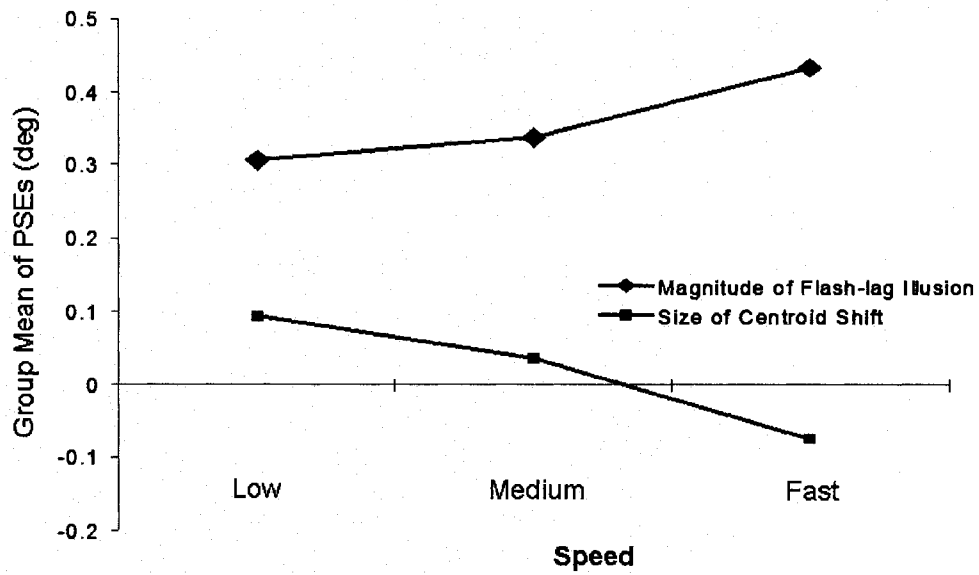


Figure 24. Comparison of the magnitude of the flash-lag illusion and the size of centroid shift across speed conditions. In all speed conditions, the size of centroid shift was smaller than that of the flash-lag illusion, which implies that the illusion cannot be explained solely by the size of the estimated centroid shift.

On the group level, the calculated centroid shifted in the direction of motion in both the low and medium speed conditions, and it shifted in the direction opposite to that of the motion in the high speed condition. The sizes were 0.09° , 0.04° and 0.07° in the low, medium and high speed conditions.

The magnitude of the flash-lag illusion and the size of centroid shift were first compared on the individual level. In the low speed condition, the centroid shift underestimated the flash-lag illusion for five of six observers (See Figure 23a). In the medium speed condition, the centroid shift underestimated the flash-lag illusion for four of six observers (See Figure 23b). In the fast speed condition, the centroid shift underestimated the flash-lag illusion for all six observers (See Figure 23c). At the group level, the size of the calculated centroid shift underestimated the flash-lag illusion at all speeds (See Figure 24).

Discussion

We have shown that flash-lag illusion cannot be explained only by motion asymmetry theory. First, we demonstrated that two predictions from the theory in the context of the flash-lag illusion were not supported by our results. The first prediction was that motion has an asymmetrical influence on the misperception of the positions of the leading and trailing edges, in that the leading edge is misperceived to a greater extent in the direction of motion than the trailing edge. However, through Experiments 1 and 2 we found that although both the leading and trailing edges were misperceived in the direction of motion, it was primarily the trailing edge that was misperceived. We also found that it was the misperception of the trailing edge that varied as a function of speed, rather than that of the leading edge. Although the misperception of edges found in our

results could also produce a centroid shift of the moving object, it was not carried by the leading edge as predicted by motion asymmetry theory. Second, we demonstrated the flash-lag illusion cannot be explained solely by the size of the estimated centroid shift. The size of the centroid shift significantly underestimated the magnitude of flash-lag illusion in all three speed conditions.

The idea that motion signals bias localization judgments and thus might account for the flash-lag illusion is not new. For example, Nijhawan (1994) suggested that the flash-lag illusion occurs because the brain extrapolates the trajectory of a moving object based on the motion information that was collected over a period of time. Eagleman and Sejnowski (2000, 2007) argued that motion information collected after the initiation of a positional inquiry (e.g., an adjacent flash) is more important in biasing the perception of the position of the moving object at the time of the flash. Our results from Experiment 3 provide evidence that motion did shift the perceived location of the moving square (in the direction of motion), which is consistent with previous accounts. However, by comparing the magnitude of the flash-lag illusion and the size of the centroid shift produced by motion, we found that the misperception of the leading and trailing edges independently produced by motion is not sufficient to account for the flash-lag illusion. Therefore, we can reject motion asymmetry theory as an account of the flash-lag illusion.

The instantaneous perceived locations of moving objects are not only shifted in the direction of motion, but it is also possible that movement also shifts the perceived location of nearby flashed objects in the direction opposite to that of the motion. There are several studies that support this idea. For example, Watanabe et al. (2001) found that if a disk was flashed at either the leading or trailing edges of a moving object, it was

misperceived as lagging behind the leading edge to a greater extent than it was for the trailing edge. They argued that this was because the motion displaced the flash differently when it was near the leading or trailing edges. Current flash-lag illusion experimental paradigms often ask, “where is the flash perceived relative to the moving object?” Questions like this make it hard to distinguish the influence of motion on the perceived position of the moving object from its effect on the flashed object. Therefore, it would be interesting to study the mislocalization of the flashed object, and to measure its absolute mislocalization by comparing it to a permanent spatial marker instead of to the moving object. Studies like this would help to examine the effect of motion on the perceived position of flashed objects and to determine if the flash-lag illusion is a combination of the misperception of both moving and flashed objects.

Another interesting question is how motion biases the perceived positions of moving objects. In our experiments, we found that it was the trailing edge that was primarily misperceived in the direction of motion. Is this misperception of the trailing edge a result of the visual system’s active extrapolation of the object’s location along the path of motion to compensate for a neural delay between the object’s current location and the time the neural signals from the object reach visual cortex? Or is it simply a byproduct of a motion deblurring mechanism? Previous studies have suggested that when an object moves, it produces a motion “smear” in the visual system (Bex, Edgar and Smiths, 1995). This motion smear is removed by a motion deblurring mechanism mainly functioning on the trailing edge to render clear vision. It is possible that the misperception in the direction of motion of the trailing edge is a result of this deblurring mechanism, which brings the perceived position of the trailing edge forward to

counteract the visual smear produced by motion. Further investigation is needed to test these two accounts and to determine why it is primarily the trailing edge whose position is misperceived.

One of the general goals of this study was to test motion asymmetry theory as a candidate for a unifying account of motion/position illusions. Our results suggest that the theory is not a unifying account. So, the question becomes “is there a unifying account of all the motion/position illusions?” Most studies have settled primarily on a spatial rather than a temporal account of these illusions. But there is still disagreement on several issues. For example, is the motion information that is collected throughout the trajectory of movement more important at some points in time than at others? How exactly does motion interact or bias the perceived locations of moving and stationary objects? Recently, a new idea has been proposed by Watanabe and Yokoi (2006). They proposed that motion could distort visual space toward a fixed point (space-distortion hypothesis) or that the space itself remains undistorted, but the perceived position of the flash is altered by the motion (position-shift hypothesis). The motion-biasing account should address the above issues more fully.

There are some limitations of the current study. First, the edges that moved in the leading and trailing conditions had width. So, technically speaking, in each edge motion condition, both leading (first bright-dark transition) and trailing (second dark-bright transition) edges were present. Although shape perception is primarily defined by the outer edges of the rectangle (its silhouette), it is still possible the presence of another edge moving edge could have interfered with our attempts to measure shape distortion. Therefore, it would be interesting to use other types of stimuli, such as solid black

rectangles, where only one edge moves at a time in each condition, to determine whether the results still hold. Second, in our experiments, the moving objects disappeared before the observers made judgments. So, there was no movement after the inquiry (the flash or the end of the trial) was initiated. Studies have shown that although the flash-lag illusion can be found in such paradigms, its magnitude is usually smaller compared to paradigms with motion that continues after the flash (Kanai, Sheth, and Shimojo, 2004). Our results, however, showed a robust flash-lag illusion even when the movement stopped at the point of the flash. We attribute this to the fact that the movement was in the visual periphery. Kanai et al. (2004) showed that a flash-lag illusion can be observed even if the movement stops at the point of the flash as long as there is position uncertainty, such as exists in the visual periphery where position acuity is degraded.

Conclusion

The present study demonstrated that motion asymmetry theory could not account for the flash-lag illusion. First, the two predictions that the theory makes in the context of the flash-lag illusion were not supported. The results showed that contrary to the predictions of the theory the position of the trailing edge was misperceived to a greater extent than the leading edge. Second, the centroid shift estimated by measuring the mislocalization of the leading and trailing edge independently was not sufficient to explain the magnitude of flash-lag illusion. The results showed that motion asymmetry theory is not a unifying account of motion/position illusions.

References

- Blakemore, C., & Sutton, P. (1969). Size adaptation: a new aftereffect. *Science*, *166*(3902), 245-247.
- Bex, P. J., Edgar, G. K., & Smith, A. T. (1995). Sharpening of drifting, blurred images. *Vision Research*, *35*(18), 2539-2546.
- De Valois, R. L., & De Valois, K. K. (1991). Vernier acuity with stationary moving gabors. *Vision Research*, *31*, 1619-1626.
- Eagleman, D., & Sejnowski, T. J. (2000). Motion integration and postdiction in visual awareness. *Science*, *287*, 2036-2038.
- Eagleman, D., & Sejnowski, T. J. (2007). Motion signals bias localization judgments: a unified explanation for the flash-lag, flash-drag, flash-jump and Fröhlich illusions. *Journal of Vision*, *7*(4), 1-12.
- Fu, Y., Shen, Y., & Dan, Y. (2001). Motion-induced perceptual extrapolation of blurred visual targets. *Journal of Neuroscience*, *21*(RC 172), 1-5.
- Hubbard, T. L. (1995). Environmental invariants in the representation of motion: Implied dynamics and representational momentum, gravity, friction, and centripetal force. *Psychonomic Bulletin & Review*, *2*(3), 322-338.
- Kirschfeld, K., & Kammer, T. (1999). The Fröhlich effect: A consequence of the interaction of visual focal attention and metacontrast. *Vision Research*, *39*, 3702-3709.
- Khurana, B., & Nijhawan, R. (1995). Extrapolation or attention shift? *Nature*, *378*, 566-566.

- McManus, I. C. (1978). The horizontal-vertical illusion and the square. *British Journal of Psychology*, *69*(3), 369-370.
- Müsseler, J., Stork, S., & Kerzel, D. (2002). Comparing mislocalization with moving stimuli: the Fröhlich effect, the flash-lag, and representational momentum. *Visual Cognition*, *9*, 120-138.
- Nijhawan, R. (1994). Motion extrapolation in catching. *Nature*, *370*, 256-257.
- Nishida, S., Motoyoshi, I., & Takeuchi, T. (1999). Is the size aftereffect direction selective? *Vision Research*, *39*, 3592-3601.
- Ramachandran, V. S., & Anstis, S. M. (1990). Illusory displacement of equiluminous kinetic edges. *Perception*, *19*, 611-616.
- Thorson, J., Lange, G. D., & Biederman-Thorson, M. (1969). Objective measure of the dynamics of a visual movement illusion. *Science*, *164*, 1087-1088.
- Tsui, S. Y., Khuu, S. K., & Hayes, A. (2007). The perceived position shift of a pattern that contains internal motion is accompanied by a change in the pattern's apparent size and shape. *Vision Research*, *47*, 402-410.
- Whitney, D. (2002). The influence of visual motion on perceived position. *Trends in Cognitive Science*, *6* (5), 211-216.
- Wetheimer, G. (1975). Visual acuity and hyperacuity. *Investigative Ophthalmology*, *14*, 570-572.
- Whitney, D., & Cavanagh, P. (2000). Motion distorts visual space: shifting the perceived position of remote stationary objects. *Nature Neuroscience*, *3*, 954-959.

- Watanabe, K., Nijhawan, R., Khurana, B., & Shimojo, S. (2001). Perceptual organization of moving stimuli modulates the flash-lag effect. *Journal of Experimental Psychology, 27* (4), 879-894.
- Watanabe, K., & Yokoi, K. (2006). Object-based anisotropies in the flash-lag effect. *Psychological Science, 17*(8), 728-735.