2005

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Citation

Vreven, Dawn L. and Verghese, Preeti. "Predictability and the Dynamics of Position Processing in the Flash-Lag Effect." *Perception* 34, no. 1 (2005): 31-44. Accessed at http://digitalcommons.framingham.edu/psych_facpub/2

Perception, 2005, volume 34, pages 31 – 44

DOI:10.1068/p5371

Predictability and the dynamics of position processing in the flash-lag effect

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Received 8 December 2003, in revised form 1 August 2004

Abstract. Several models have been proposed to account for the flash-lag effect. One criterion for evaluating alternative models is to consider the separate effects of motion predictability and flash predictability. We first established that flash predictability has an impact on the size of the perceived spatial offset in the flash-lag illusion. We then examined motion predictability by varying the consistency of the motion trajectory. Both manipulations affected the magnitude of the flash-lag illusion. These outcomes suggest that the perception of position is a dynamic process that can be modulated by explicit cues in advance of the flash and by the temporal integration of position information over a consistent motion trajectory. A complete explanation of the flash-lag effect must specify how flash predictability and motion predictability modulate position-processing mechanisms.

1 Introduction

The flash-lag illusion occurs when an observer judges the position of a briefly flashed stationary object relative to the position of a continuously visible moving object. Observers report the flashed object to spatially lag behind the moving object even when the two objects are physically aligned.

There are three broad categories of explanation for the flash-lag effect. The first, Nijhawan's (1994) motion-extrapolation hypothesis, proposes that the visual system spatially extrapolates the position of a moving object to compensate for the inevitable neural delays that occur as visual information is transduced. A number of studies, however, have provided data incompatible with this hypothesis (Whitney and Murakami 1998; Brenner and Smeets 2000; Whitney et al 2000a).

A second category of explanation for the flash-lag effect is that of differential latencies. According to this hypothesis, there is a reduced neural delay for processing moving stimuli relative to static stimuli, making the flash appear to lag behind the moving object (Purushothaman et al 1998; Whitney et al 2000b; Murakami 2001a). A great deal of experimental evidence has shown that manipulations that affect visual latency affect the perceived positions of objects. It is well established, for example, that visual latency varies inversely with luminance (Roufs 1963; Williams and Lit 1983). Regarding the flash-lag effect in particular, Purushothaman et al varied the contrast of the flash and moving object. They found that the typical flash-lag effect, in which the static object appears to lag behind the moving object, could be converted into a flash-lead effect if the luminance of the moving object was low relative to the luminance of the stationary flashed object. Similar results have been reported by others (Lappe and Krekelberg 1998). There are a number of variants of the differential-latency hypothesis. One variant hypothesizes that the neural delays are modulated by shifts in attention (Baldo and Klein 1995; Baldo et al 2002). Other variants of the differential-latency hypothesis propose a stage of temporal integration of the position of the moving object in addition to a neural latency difference between the moving and static objects. Whitney et al (2000b), for example, propose that the inherent neural latency difference between the moving and static objects is 100 ms, and that the moving object has a temporal integration window of around 45 ms. Patel and colleagues (Patel et al 2000; Ogmen et al 2004) posit that some portion of the latency difference between the position computation for moving and static objects can be induced by the 'dynamics' of position processing. According to these authors, the position of a moving object is determined by a transient phase lasting 75 – 100 ms followed by a steady-state phase. Large offsets in the perceived positions of the static and moving objects occur during the transient phase; when the system reaches steady state, the perceived offset is constant and dependent on differential latency alone.

A third category of explanation for the flash-lag effect emphasizes a process of positional averaging over time (Krekelberg and Lappe 1999, 2000; Eagleman and Sejnowski 2000a, 2000b). According to Eagleman and Sejnowski's postdiction hypothesis, the final position of an object is determined by averaging several samples of the instantaneous position of the object over time. The temporal window during which positional averaging occurs, however, is not symmetric around the spatiotemporal position of the flash. Thus, samples of the position of the moving object may include positions at the time of the flash and positions up to 80 ms after the flash. This positional averaging process yields a veridical estimate of the position of the static flash, but the estimate of the position of the moving object is biased towards positions occupied after the flash. Krekelberg and Lappe (2000) propose a similar mechanism in which the perceived difference in position between the flash and the moving object is a temporal average of the difference in position beginning at the time of the flash and extending as long as 500 – 600 ms.

One issue that is only beginning to be addressed in the published literature on the flash-lag effect is the role of stimulus predictability. The study of predictability in the flash-lag effect has been problematic for several reasons. First, 'predictability' has been defined very differently by different investigators. Sometimes it refers to explicit spatial and/or temporal cues; in other work, predictability refers specifically to the motion trajectory. Second, the experimental paradigms in some investigations of the flash-lag effect have varying amounts of inherent (and presumably unintentional) predictability of either the flash or the motion. A review of the experiments on predictability can be divided into studies of flash predictability and studies of motion predictability.

1.1 *Manipulations of flash predictability*

The conclusion from studies of flash predictability is somewhat consistent: making the flash spatially predictable, whether implicitly through repetition or explicitly with a luminance cue, decreases the magnitude of the illusion. Using rotary motion, Brenner and Smeets (2000) provided an explicit luminance cue on the computer screen indicating the spatial position at which the flash would occur. In this case, the magnitude of the illusion fell to zero for the two authors and decreased significantly for two naïve subjects. The conclusion is that the magnitude of the flash-lag illusion is affected by observers' anticipation of the spatial position of the flash. As the authors note, this outcome is inconsistent with the idea of a fixed latency difference between the responses to the motion and the flash. One potential problem with this work, however, is that the luminance cue, which persisted on the screen during the trial, could have affected position processing. It is possible that the luminance of the cue increased the effective luminance of the static flash. Increasing the effective luminance of the flash can cancel or even reverse the flash-lag effect. Thus, it is not clear whether Brenner and Smeets are measuring the effect of an explicit cue to flash position or the effect of increasing the luminance of the moving object.

Eagleman and Sejnowski (2000b), also using rotary motion, compared the magnitude of the flash-lag illusion when the flashes appeared every 2000 ms to the magnitude when the flashes appeared randomly 1500 to 2500 ms after the previous flash. In the former condition, the flash was completely spatiotemporally predictable; in the latter, the flash was spatiotemporally unpredictable (although observers knew that it would appear within a 1000 ms window). They found a greater magnitude of illusion when the flashes were unpredictable, consistent with Brenner and Smeets (2000).

Baldo et al (2002) manipulated the predictability of flash eccentricity in an experiment in which a dot followed a circular trajectory around a fixation point. The flash appeared in the same angular position on every trial after either two or three revolutions. In some blocks of 50 trials, the eccentricity of the flash from the fixation point was held constant at either 1.7 deg or 3.9 deg. In other blocks of trials, the flash appeared randomly at either 1.7 deg or 3.9 deg eccentricity. Baldo et al found a significant decrease in the size of the flash-lag illusion when the flash eccentricity was predictable. Note that, although the eccentricity of the flash was varied in Baldo et al's experiment, its angular position was the same on every trial. Further, the temporal predictability of the flash was also high. If the flash failed to occur in the second rotation, it was certain to occur in the third.

1.2 *Manipulations of motion predictability*

Studies by Whitney and colleagues (Whitney et al 2000a, 2000b) suggest that unpredictable changes in motion direction and speed have little effect on the magnitude of the flash-lag illusion. Whitney et al manipulated motion predictability in the flash-lag effect by introducing a single, abrupt change in motion direction and/or speed. In their studies, a 'bar' translated horizontally across a computer screen. The flash occurred at a random spatiotemporal position on each trial. The authors measured the magnitude of the illusion by varying the position of the flash relative to alignment with the bar. Within an 80 ms window around the change in bar speed, the magnitude of spatial mislocation was somewhat variable. Outside of this window, however, the magnitude of the mislocation was constant and proportional to the speed of bar motion. In other work these authors showed that an unpredictable change in motion direction did not affect the magnitude of the illusion outside of a roughly 80 ms window around the time of direction change. The conclusion was that motion predictability had little or no effect on the magnitude of the illusion and that the position mislocation "... appears to be omnidirectional rather than specific to a predictable motion trajectory".

Murakami's work also suggests that the predictability of a motion sequence has little effect on the magnitude of the flash-lag illusion. Murakami (2001a, 2001b) developed a 'random motion' stimulus to measure the perception of position under conditions of high spatial uncertainty for the motion and high temporal uncertainty for the flash. The moving bar in this stimulus jumped to a new position, somewhere within a central 2.5 deg window, every 167 ms. The flash was presented within 0.83 deg of fixation at random intervals centered on 3 s (±1 s). The observer's task was to indicate whether the flash appeared to the left or to the right of the bar. The random-motion paradigm revealed an approximately 80 ms flash-lag effect under these conditions. Consider, however, that the spatial and temporal parameters in the random-motion stimulus would necessarily result in some bar displacements unlikely to be perceived as smooth motion. The 2.5 deg spatial displacement, for example, is far beyond the typical value of $d_{\max}$ (Braddick 1974). Further, because the bar was static for 167 ms after each jump, it is possible that observers were judging the relative positions of a static flash with a static bar.

A third and final reason that studies of motion predictability are problematic is that predictability has often been manipulated for the specific purpose of arguing against a particular hypothesis. Manipulations of motion predictability, for example, have been used exclusively to argue against the spatial-extrapolation hypothesis; manipulations of flash predictability have been used to argue against the postdiction hypothesis

(Chappell and Hine 2004). Rather, it may be more useful to consider how some of the differential-latency and temporal-integration hypotheses outlined above can be distinguished on the basis of stimulus predictability.

A strict differential-latency model would predict no effect of either flash or motion predictability on the magnitude of the flash-lag effect. Consider, however, the multiple-channel differential-latency theory of Patel and colleagues (Ogmen et al 2004), which proposes a transient phase and a steady-state phase for computing the position of a moving object. Once the position computation process is in steady-state, the lag should be constant for consistent motion. Thus, this version of the differential-latency model predicts that consistent (predictable) motion trajectories should yield a constant flash-lag size after some amount of time, typically on the order of 200 ms. The model has no clear predictions regarding flash predictability.

Eagleman and Sejnowski's (2000b) postdiction model posits that a salient flash starts the motion position computation process. Thus, advance information about the spatiotemporal position of the flash should not affect the size of the illusion if the information does not change the salience of the flash. Likewise, the consistency of the motion trajectory before the flash should have no effect on the size of the illusion. Krekelberg and Lappe's (2000) temporal-recruitment hypothesis is based upon a very long (500 – 600 ms) temporal average of the difference between the position of the flash and the moving object. This model predicts a decreasing flash-lag effect with longer exposures to consistent motion. However, explicit high-level cues to the position of the flash would not be expected to alter the magnitude of the illusion.

In short, the available evidence on the role of spatiotemporal predictability in position processing is not always clear nor is it complete. The current work was an attempt to clarify and compare the role of different types of predictability on the magnitude of the flash-lag illusion. The experiments reported here dissociate flash predictability and motion predictability in the same paradigm. Spatial and temporal flash predictability are treated separately. The aim was to determine how predictability affects the computation of position and allows for separate contributions for different types of predictability. Such data are required to determine how the effects of predictability can be incorporated into models of the flash-lag effect. In the current set of experiments we examine the effect of predictability in the flash-lag illusion in two ways: first, by providing explicit cues to the spatial and/or temporal position of the flash; and, second, by using either a predictable or unpredictable motion sequence.

2 Experiment 1: Predictable rotary motion

2.1 *Method*

2.1.1 *Observers and equipment.* Three observers with corrected-to-normal vision participated in this experiment. Observer DV was an author; observers BL and LC were naïve. Stimuli were presented on a 16 in CRT monitor (Mitsubishi Diamond Pro 74SB, 1024 × 768 pixels, refresh rate 75 Hz) and controlled by an Apple Power Macintosh. The experiments were programmed with MATLAB (The Mathworks, Inc.) and the 'psychophysics toolbox' (Brainard 1997; Pelli 1997).

2.1.2 *Stimulus.* The stimulus consisted of a group of three white dots (diameter 0.5 deg, luminance 170.2 cd m^{-2}) separated by 3.5 deg on a dark-grey (15.3 cd m^{-2}) background, forming a 'bar' (figure 1). The central dot was stationary, and the outer two dots followed a circular trajectory around the center dot at a rate of 1 Hz. The center-to-center spacing of the dots was 2 deg. With a frame rate of 75 Hz and a stimulus duration of 1 s, the dots moved at an angular speed of 4.8° per 13.3 ms frame. The start angle of the bar and the direction of motion (clockwise or counterclockwise) was random on every trial. Observers viewed the displays binocularly from a distance of 57 cm.

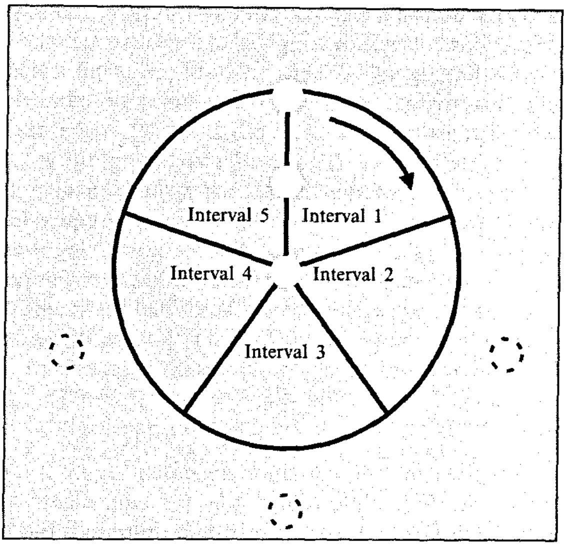

Figure 1. Schematic depiction of the stimulus. Three dots forming a 'bar' rotated once either clockwise or counterclockwise around the central dot at a speed of 1 Hz. The trajectory of the outermost dot is shown as a circle (which did not appear in the stimulus display). We call each 200 ms (15 frame) sector of the stimulus an interval. The flash dot appeared randomly in the temporal center of either interval 2, 3, or 4 (dashed circles). The spatial position of the flash was manipulated relative to the spatial center of the sector in order to measure a psychometric function.

Observers were instructed to maintain fixation on the central dot of the bar, and to strike a key to start the motion. After a 500 ms delay, the bar began to rotate. During the rotation, a flash dot appeared for 1 frame (13.3 ms). The flash dot was identical in size and luminance to the dots of the bar with a consistent 2 min of arc center-to-center spacing from the outermost bar dot. The task was to indicate whether the flash appeared to lead or lag the rotating bar. After one complete rotation, the screen remained blank until the observer responded. Trials were self-paced.

The circle swept out by the motion of the bar can be idealized as consisting of five equally spaced 200 ms (15 frame) duration 'intervals'. The flash dot appeared temporally in the center of either interval 2, 3, or 4. Thus, the flash appeared randomly and equally often either 300, 500, or 700 ms after the onset of motion. This manipulation ensures that the observer could not predict either the location of the flash or its timing before the start on each trial. The spatial position of the flash was manipulated relative to the spatial center of an interval to generate a psychometric function. Five spatial positions were used, ranging ±14.4 deg (±3 frames) from the center of a sector. The range of positions was adjusted for each observer. A complete psychometric function was generated for each interval in which a flash appeared.

2.1.3 *Flash-cue conditions.* Four flash-cue conditions were run: no cue, spatial cue, temporal cue, and both cues. In the spatial-cue condition, the flashed dot was presented in the spatial position at which it would appear during the trial, along with the bar in a random start angle position. Once the observer struck a key to begin the trial, all stimuli disappeared for 500 ms before the trial continued. This procedure was meant to decrease the likelihood that the luminance of the pre-trial spatial cue would interact with the presentation of the flash during the trial. In the temporal-cue condition, a series of 5 beeps were presented, each temporally aligned with the center of one interval. Thus, one of the beeps (in interval 2, 3, or 4) occurred at exactly the same time as the flash. In the both-cues condition, the explicit luminance cue and the beeps were presented to observers.

2.1.4 *Data analysis.* Data were analyzed separately for each combination of flash cue and interval. The data were fit with a weighted cumulative normal function with the use of probit analysis (Finney 1971). This analysis yields an estimate of the mean (bias) and threshold (sensitivity). The mean is the point of subjective equality (PSE); it is the point at which the flash and the motion appear to be aligned. Thus, it is a measure of the size of the illusion. Because the spatial position of the moving bar was correlated with the timing of the flash, each spatial mean and threshold has a temporal equivalent. For convenience, both the spatial and equivalent temporal PSEs and thresholds are given. By convention, spatial/temporal positions that lag behind physical alignment are assigned negative numbers and spatial/temporal positions that lead alignment are assigned positive numbers. Each fitted mean and threshold is based on a minimum of 150 observations (2 sessions). Data were discarded if the resulting psychometric functions did not pass a χ^2 goodness-of-fit test. Error bars are standard errors of the mean.

2.2 *Results*

Thresholds for each observer in each condition appear in figure 2. The average threshold across all observers and conditions was 5.8°, or equivalently, 16.08 ms. A 4×3 (cue × interval) within-subjects ANOVA confirmed that thresholds did not differ by either cue ($F_{3,6} = 2.56$, $p = 0.24$) or by interval ($F_{2,4} = 10.63$, $p = 0.08$); the interaction of cue and interval was also non-significant ($F_{6,12} = 2.29$, $p = 0.53$). Thus, observers were consistently sensitive in all conditions.

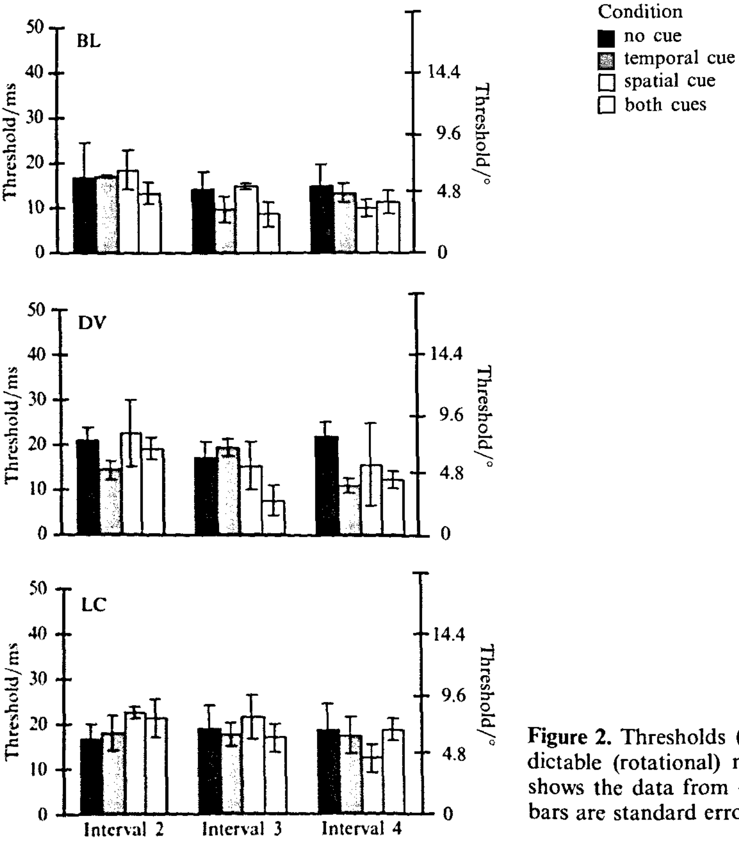

Figure 2. Thresholds (sensitivity) for predictable (rotational) motion. Each panel shows the data from one observer. Error bars are standard errors of the mean.

Figure 3 shows the PSEs for each observer in each condition. Negative numbers indicate perceived spatial/temporal lags for the flash; positive numbers indicate spatial/temporal leads. A 4 × 3 (cue × interval) within-subjects ANOVA was performed on the data. The average PSE across all observers and conditions was −3.36° (−9.32 ms). There are several outcomes worth noting. First, the main effect of cue was significant ($F_{3,6} = 16.22$, $p = 0.04$). A trend analysis on the cue data indicated a significant linear trend ($F_{1,2} = 141.53$, $p = 0.007$), where the magnitude of the illusion is greatest in the no-cue condition, followed by the temporal-cue, spatial-cue, and both-cues conditions, in that order. Second, the main effect of interval was significant ($F_{2,4} = 29.3$, $p = 0.01$). This indicates that the interval in which the flash appeared had a profound effect on the magnitude of the illusion. The flash-lag effect was largest (−17.76 ms averaged over participants and cue conditions) when the flash appeared in interval 2, 300 ms after the start of the motion. The illusion was intermediate in size (−8.87 ms) when the flash appeared 500 ms after the start of motion (interval 3), and was smallest (−1.32 ms) when the flash appeared 700 ms after the start of motion (interval 4). The interaction of cue and interval was not significant ($F_{6,12} = 1.18$, $p = 0.40$).

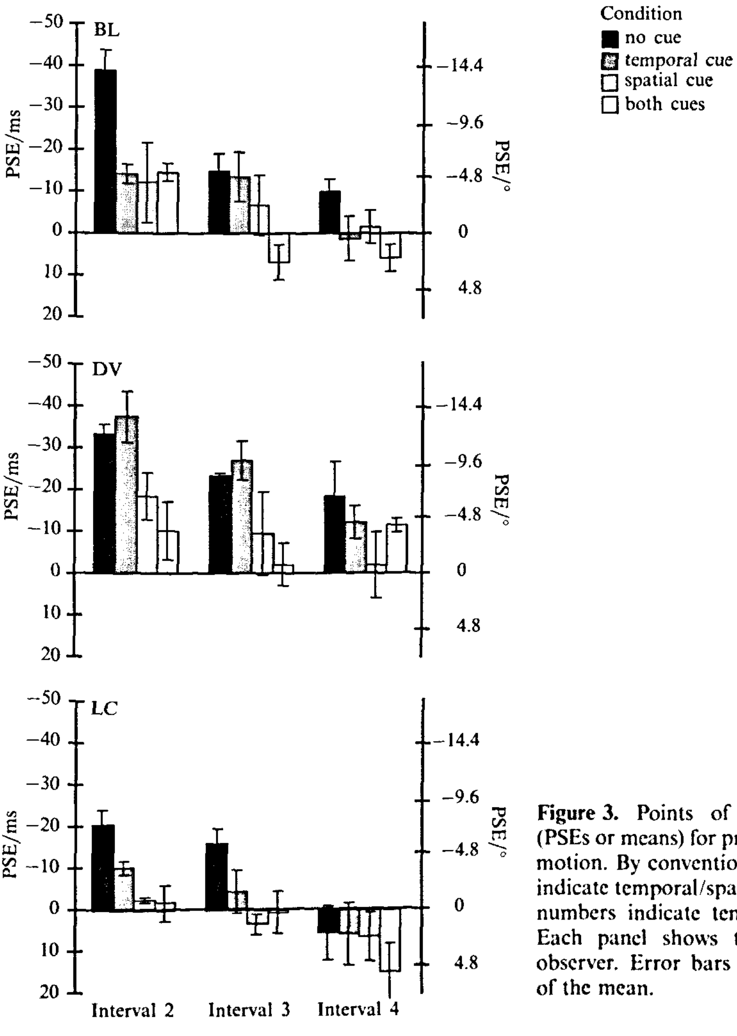

Figure 3. Points of subjective equality (PSEs or means) for predictable (rotational) motion. By convention, negative numbers indicate temporal/spatial lags and positive numbers indicate temporal/spatial leads. Each panel shows the data from one observer. Error bars are standard errors of the mean.

2.3 *Discussion*

Experiment 1 demonstrated that cues to the spatiotemporal position of the flash increase flash predictability and decrease the magnitude of the flash-lag illusion. Flash predictability was manipulated by explicitly cueing its spatial position, its temporal position, or both. These explicit cues reduced the magnitude of the flash-lag illusion relative to a no-cue condition, and the effect of both cues together was approximately additive. The spatial cue was found to reduce the size of the illusion significantly more than the temporal cue. One reason the temporal cue may not have been as effective in reducing illusion size is that the beeps of the temporal cue did not predict the time of the flash as effectively as the spatial cue predicted its position. Additionally, there was less inherent uncertainty about the timing of the flash than about its spatial position. Consider that the flash always occurred at the temporal center of each interval. The spatial position of the flash, however, was varied about the spatial center of each interval.

The magnitude of the flash-lag illusion was measured at three intervals: either 300, 500, or 700 ms after the start of motion. This manipulation was meant to ensure that the observer was uncertain about the position and timing of the flash before the start of motion on each trial. Interestingly, the magnitude of the illusion decreased as the interval in which flash appeared increased. We call this the 'interval effect'.

What is the origin of the interval effect? The interval effect could simply reflect the fact that the flash becomes more predictable over time. If the flash does not occur in interval 2 or 3 (300 or 500 ms after the onset of motion), it is certain to occur in interval 4 (700 ms after the onset of motion). If this hypothesis is correct, then the observed interval effects are due solely to the inherent flash predictability implicit in the experimental paradigm.

Krekelberg and Lappe (2000) report a similar effect in their studies of the flash-lag effect, and attribute it to position integration over time. The longer a consistent trajectory is visible, the more precise the difference in position signals for the flash and the moving object becomes. If this explanation is correct, it underscores the importance of position integration in explaining the flash-lag effect.

The interval effect is not consistent with either a strict version of differential-latency theory or with Ogmen et al's (2004) multiple-channel version. Both models predict a constant magnitude of flash-lag effect after approximately 200 ms. To account for these data, differential-latency theories would have to assume that observers are able to attend to the flash as it becomes more predictable and that this reduces the processing time for the flash.

One way to test these hypotheses is to decrease the consistency of the motion trajectory. This manipulation would reduce the effectiveness of integrating motion over a long temporal window, but would leave the implicit predictability of the flash intact. If the interval effect is due to flash predictability, manipulations of the motion trajectory should have no effect on the magnitude of the illusion over intervals. Instead, if the interval effect is due to motion predictability, then manipulating the consistency of the trajectory of motion should greatly reduce the interval effect.

3 Experiment 2: Unpredictable random-velocity motion

In this experiment we examined the interval effect found in experiment 1. The primary issue is whether the interval effect is due to flash predictability or motion predictability. The logic is straightforward: if the interval effect is due to flash predictability, then manipulating the consistency of the motion trajectory should leave the effect intact.

3.1 *Method*

The equipment, observers, task, and cue conditions were identical to those in experiment 1, with a single exception—the consistency of the rotational motion. As in experiment 1, the bar motion can be idealized as consisting of five 200 ms (15 frame) duration intervals. In this experiment, the velocity of the bar rotation changed in the first frame of every interval. Thus, either the speed of motion or the direction of motion or both changed every 200 ms. The probability of a direction change every 200 ms was 0.5, and the probability of a speed change every 200 ms was 1. Speeds were drawn from a uniform distribution with the lower bound of 2.4° s^{-1} and an upper bound of 9.6° s^{-1}. These speeds are twice as slow and twice as fast, respectively, as the speed in experiment 1. Because the trial duration was 1 s, velocity changed five times per trial (once at the onset of motion and once at the first frame of the remaining four intervals). The bar motion was continuous with no jumps; a velocity change simply altered its speed or direction. As in experiment 1, the flash dot appeared temporally in the center of interval 2, 3, or 4. Thus, as before, the flash appeared either 300, 500, or 700 ms after the onset of motion.

3.2 *Results and discussion*

Thresholds for each observer in each condition appear in figure 4. The average threshold across all observers and conditions was 12.77° or, equivalently, 35.38 ms. Thresholds were both higher and more variable in the random-velocity condition than in the rotation condition, indicating that the task was more difficult. As before, a 4 × 3 (cue × interval) within-subjects ANOVA confirmed that thresholds did not differ by either

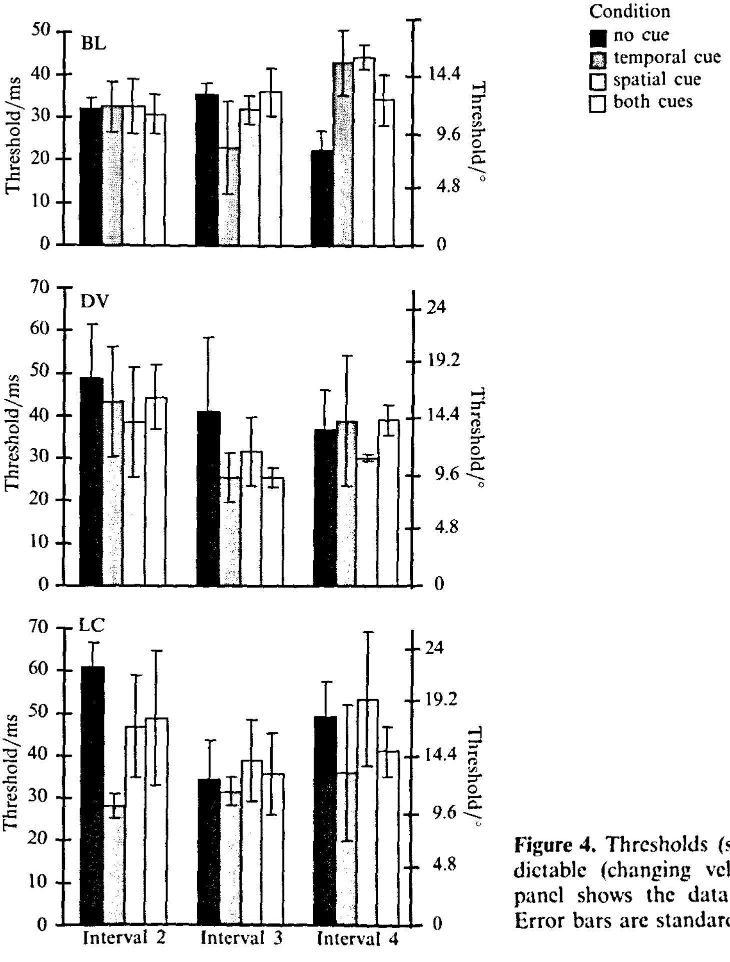

Figure 4. Thresholds (sensitivity) for unpredictable (changing velocity) motion. Each panel shows the data from one observer. Error bars are standard errors of the mean.

cue ($F_{3,6} = 2.61$, $p = 0.24$) or by interval ($F_{2,4} = 3.91$, $p = 0.15$); the interaction of cue and interval was also non-significant ($F_{6,12} = 1.19$, $p = 0.39$). Thus, observers were consistently sensitive in all conditions.

Figure 5 shows the PSEs for each observer in each condition. Negative numbers indicate perceived spatial/temporal lags for the flash; positive numbers indicate spatial/temporal leads. The magnitude of the illusion averaged over observers and conditions decreased from −9.32 ms (−3.36°) with predictable rotation to −5.8 ms (−2.09°) with unpredictable changing velocity motion. A 4 × 3 (cue × interval) within-subjects ANOVA showed that the interval effect was not significant ($F_{2,4} = 0.82$, $p = 0.17$). The analysis also confirmed that the cue effect was no longer significant ($F_{3,6} = 3.42$, $p = 0.47$).

The interval effect obtained with consistent motion was no longer discernible with random-velocity motion. Position averaging mechanisms can explain this result if one assumes that random-motion trajectories do not capture the dynamics of position processing for consistently moving objects. Rather, random motion necessarily limits the spatiotemporal integration of a motion signal. It is likely that the abrupt change in velocity and direction of the motion trajectory resets the temporal integration window.

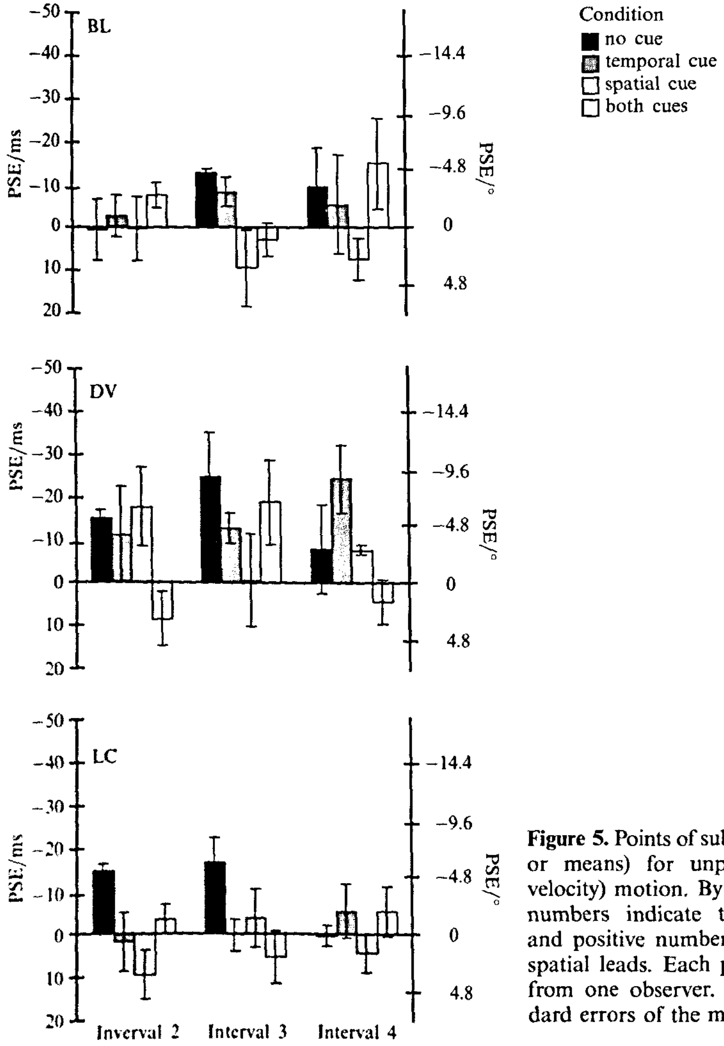

Figure 5. Points of subjective equality (PSEs or means) for unpredictable (changing velocity) motion. By convention, negative numbers indicate temporal/spatial lags and positive numbers indicate temporal/spatial leads. Each panel shows the data from one observer. Error bars are standard errors of the mean.

Random-velocity motion decreased the overall magnitude of the illusion relative to consistent trajectory motion. Why? One possibility is that the size of the flash-lag illusion is known to vary approximately linearly with the velocity of the motion (Krekelberg and Lappe 1999). The illusion magnitudes we report are averaged over velocity. However, the velocity on any particular trial was drawn from a uniform distribution containing speeds from twice as slow to speeds twice as fast as those used in experiment 1. The average speed of this uniform distribution is therefore the same as the speed used in experiment 1. Thus, the average illusion size should be the same as in experiment 1. But it is not; it is smaller, suggesting that perhaps random motion is a poor motion signal compared to the consistent motion trajectory of experiment 1. This reasoning suggests that the decrease in illusion magnitude with random velocity is due to a floor effect caused by the limited amount of position integration possible with random motion. This possibility is explored in experiment 3. Another possibility for the reduced flash-lag effect with random motion is suggested by the data of Whitney et al (2000a). They show that when there are abrupt reversals in motion direction, the spatial flash-lag is considerably reduced and may even become a spatial lead within about 45 ms of the time of the direction change. If these leads are averaged with the usual lags seen at steady state, it would reduce the overall magnitude of the flash-lag effect. This is unlikely to be an explanation for the reduced flash-lag in the current experiment, however, because our flash always occurred 100 ms before or after a speed or direction change.

Finally, cues for the spatiotemporal position of the flash were ineffective with random motion. This is a somewhat surprising result, because the flash presentation was identical to that of experiment 1. This outcome suggests that it is the determination of motion position, and not flash position, that limits performance. It is also possible that the spatial cue, in particular, was more informative with the consistent motion of experiment 1 compared with the random-velocity motion of experiment 2. In experiment 1, the spatial location of the flash also revealed its temporal location after the start of motion. In experiment 2, however, the spatial cue did not predict when the flash would occur because of speed and/or direction reversals.

4 Experiment 3: Strobe motion

One could argue that the lack of effect for either the cue or the interval in experiment 2 is due to a poor motion signal, independent of the predictability of the flash. Consider, for example, that each interval consists of 15 frames (200 ms). The flash appears at ±3 frames from the spatial center of the interval in order to generate the psychometric function. Thus, some flashes occur only 4 frames (about 53 ms) after a change in direction and/or speed. This is well below some estimates of the integration time of motion detectors (Watson and Turano 1995). Such an explanation might also account for the elevated thresholds and high variability of the magnitude of the illusion in experiment 2 relative to experiment 1. To address this issue, we measured the magnitude of the illusion in the absence of motion. This was achieved by presenting the bar for one frame at the spatiotemporal center of each interval. The perceptual consequence of this manipulation was that the bar appeared to 'strobe' rather than move smoothly from one position to the next. Because the bar appeared on the same frame as the flash, there was no relative motion between the bar and the flash. The direction and speed of the implied motion of the bar were identical to those in experiment 1. Two flash-cue conditions were run: no cue and both cues. Two observers, BL and DV, served in this experiment.

If the results of experiment 2 can be attributed to a poor motion signal, then we should expect strobe motion to produce similar data: specifically, high and variable thresholds, small flash-lag illusions, and no effects of interval or cue.

4.1 *Results and discussion*

Thresholds for the two observers in the two flash-cue conditions appear in the left panels of figure 6. The average threshold across observers and cue conditions was 12.7 ms, or equivalently 4.6°, considerably lower than the thresholds obtained with changing-velocity motion (35.38 ms or 12.77°). This indicates that observers were more sensitive to the spatiotemporal position of the flash when there was no relative motion between the flash and bar. The right panels in figure 6 shows the PSE data. The overall magnitude of the illusion decreased from −5.8 ms (−2.09°) with changing-velocity motion to −1.60 ms (0.57°) with strobe motion. As before, 4 × 3 (cue × interval) within-subjects ANOVAs were completed on the threshold and PSE data. No significant effects were found.

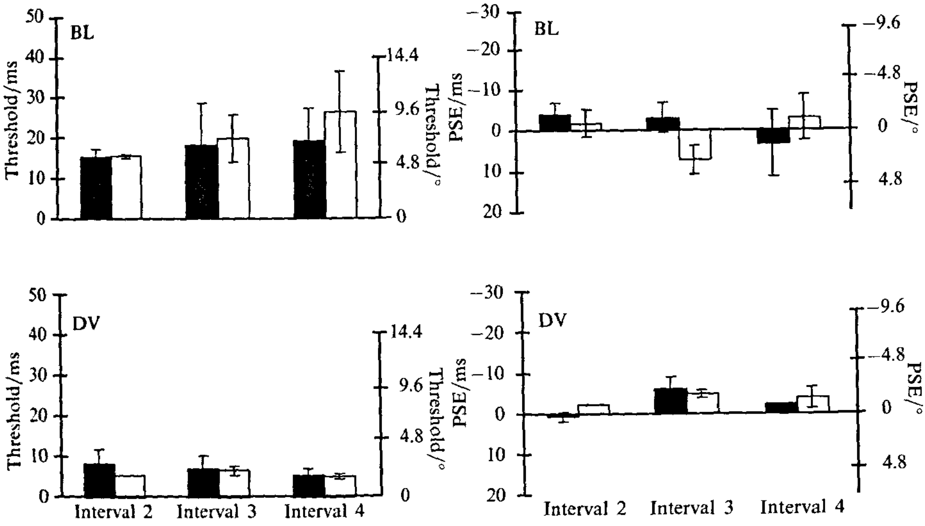

Figure 6. Thresholds (left panels) and means/PSEs (right panels) for strobe motion. Conventions are the same as in figures 2–5.

The results of experiment 3 are quite different from those of experiment 2. The current experiment presented an extremely impoverished motion signal because the motion of the bar was visible only for one frame every 200 ms. Observers achieved the best position sensitivity in this case, as the thresholds were lower for strobe motion than for either rotation or changing-velocity motion. The size of the position illusion was also reduced to nearly zero. Because the motion is strobed once every 200 ms and there is about 72° displacement between successive strobe positions, it is likely that the strobed stimulus is perceived more as a flash. This might account for the lack of the position illusion between the strobed motion and the flash. This is different from the case in experiment 2, where the motion signal, although random, is robust and the flash-lag illusion was clearly different from zero.

5 General discussion

Experiment 1 demonstrated that the magnitude of the flash-lag illusion can be decreased by providing explicit cues to the time and/or position of the flash. The experiment also suggests that cues to spatial position are more effective in reducing illusion magnitude than cues to temporal position. The modulation of the flash-lag effect by manipulations of flash predictability cannot be accounted for by current versions of differential-latency theories. Such theories do not specify how the visual latency for a flashed object could be affected by advance knowledge of the timing and/or position of the flash. To account for these data, differential-latency theories would have to assume that observers are able to better attend to the flash as it becomes more predictable and that this reduces the processing time for the flash. The results also cannot be accounted for by theories of positional averaging, which currently have no mechanism for incorporating flash predictability.

Experiment 1 also revealed an interval effect, in which the magnitude of the flash-lag illusion decreased as the flash appeared later in the trial. This outcome is inconsistent with both strict differential-latency theories and with the multiple-channel differential-latency theory. It is consistent with models of positional averaging, and suggests that position integration occurs on very long time scales, up to 700 ms.

Experiment 2 demonstrated that the consistency of the motion trajectory affected the magnitude of the illusion. In this experiment, motion trajectories were limited to 200 ms of consistent motion before an unpredictable change in velocity occurred. Interestingly, motion with this kind of unpredictable trajectory decreased the magnitude of the flash-lag illusion. Further, the stimulus used in experiment 3 prevented any relative motion between the bar and the flash, and resulted in illusion magnitudes near zero. One interpretation of these outcomes is that the position integration window for the moving object systematically varied from experiment 1 to experiment 3. For the consistent-trajectory motion, the size of the integration window was limited only by the duration of the trial. Experiments 2 (random-velocity motion) and 3 (strobe motion) forced the position integration window to be small, and illusion size was consequently small. This interpretation is consistent with the finding that as a flash is strobed such that its spatiotemporal properties become more similar to a consistently visible moving object, the less the magnitude of the flash-lag effect (Krekelberg and Lappe 1999). This outcome suggests that the *smaller* the position integration window for a moving object, the more like a static object it becomes and the more precise its position estimate. Differential latency can also explain why there is no flash-lag effect when the motion is strobed. In this case the comparison may be effectively between two stimuli that are flashed, and thus there might not be differential latency between them.

Does uncertainty about the flash contribute separately to the magnitude of the flash-lag effect, or does information about the flash affect the size of the position integration window for the moving object? Note that the flash cues were not effective in experiments 2 and 3. One explanation for this may be that the integration window was already so small that no modulation was possible.

The typical stimulus used to measure the flash-lag illusion contains motion along a predictable path and a flashed stimulus that is presented at an unknown location and time. It is possible that the increased lag of the flash with respect to predictable motion occurs because a predictable stimulus has a higher *effective* contrast than an unpredictable stimulus. Verghese and McKee (2002), for example, showed that the contrast required to detect a motion signal in noise was greater at the beginning of a 200 ms motion sequence than at the end. They attributed this to high position and direction uncertainty at the beginning of the motion sequence compared to the end. This is analogous to the high uncertainty of the flash in typical flash-lag studies and the low uncertainty of the moving stimulus. Therefore, the flash-lag illusion could be due to the higher effective contrast (and the accompanying reduction in latency) of a stimulus moving along a predictable path as compared to a static flash whose location and timing are uncertain.

What is the impact of this work on theories of position processing? The current work highlights the dynamics of a position integration process which occurs with consistently visible motion along a predictable trajectory. We have also shown that the flash-lag effect depends on flash uncertainty. Our study suggests that current models need to incorporate both the effects of flash predictability as well as motion predictability.

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