Perception, 2002, volume 31, pages 17 – 30

DOI:10.1068/p3302

Evidence for an attentional component of the perceptual misalignment between moving and flashing stimuli

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Received 19 March 2001, in revised form 7 September 2001

Abstract. If a pair of dots, diametrically opposed to each other, is flashed in perfect alignment with another pair of dots rotating about the visual fixation point, most observers perceive the rotating dots as being ahead of the flashing dots (flash-lag effect). This psychophysical effect was first interpreted as the result of a perceptual extrapolation of the position of the moving dots. Also, it has been conceived as the result of differential visual latencies between flashing and moving stimuli, arising from purely sensory factors and/or expressing the contribution of attentional mechanisms as well. In a series of two experiments, we had observers judge the relative position between rotating and static dots at the moment a temporal marker was presented in the visual field. In experiment 1 we manipulated the nature of the temporal marker used to prompt the alignment judgment. This resulted in three main findings: (i) the flash-lag effect was observed to depend on the visual eccentricity of the flashing dots; (ii) the magnitude of the flash-lag effect was not dependent on the offset of the flashing dot; and (iii) the moving stimulus, when suddenly turned off, was perceived as lagging behind its disappearance location. Taken altogether, these results suggest that neither visible persistence nor motion extrapolation can account for the perceptual flash-lag phenomenon. The participation of attentional mechanisms was investigated in experiment 2, where the magnitude of the flash-lag effect was measured under both higher and lower predictability of the location of the flashing dot. Since the magnitude of the flash-lag effect significantly increased with decreasing predictability, we conclude that the observer's attentional set can modulate the differential latencies determining this perceptual effect. The flash-lag phenomenon can thus be conceived as arising from differential visual latencies which are determined not only by the physical attributes of the stimulus, such as its luminance or eccentricity, but also by attentional mechanisms influencing the delays involved in the perceptual processing.

1 Introduction

A moving object is generally perceived as spatially leading a brief flash presented adjacent to it, therefore shifted forward along its trajectory (figure 1). This so-called flash-lag illusion has been interpreted as a misperception of the relative position between moving and static objects, and has received different explanations (Nijhawan 1994; Baldo and Klein 1995; Lappe and Krekelberg 1998; Purushothaman et al 1998; Whitney and Murakami 1998; Eagleman and Sejnowski 2000a; Krekelberg and Lappe 2000, 2001; Whitney et al 2000). Nijhawan (1994) originally interpreted the flash-lag effect as resulting from a spatial extrapolation of the moving object. There is a delay intrinsic to the processing of any visual stimulus, during which a significant distance can be traveled by a moving object, leading to a discrepancy between its actual and perceived location. Therefore, Nijhawan hypothesized that the visual system might use the predictability of the trajectory of a moving stimulus to extrapolate its future location. The perceptually extrapolated position of a moving object would thus compensate for the spatial error introduced by delays a signal must incur on its way from retina to cortex. Two years earlier, Emerson and Pesta (1992) had proposed an identical mechanism of motion extrapolation as part of an explanation for the Pulfrich phenomenon.

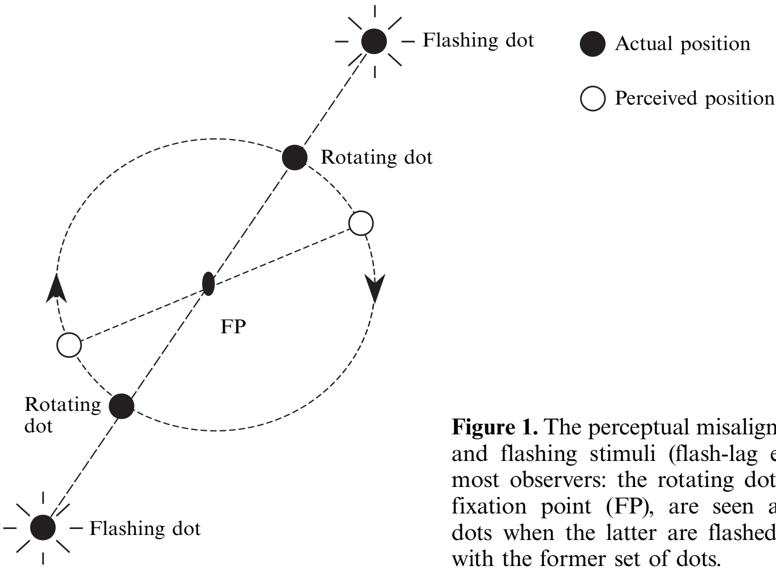

Figure 1. The perceptual misalignment between moving and flashing stimuli (flash-lag effect) as reported by most observers: the rotating dots, moving around the fixation point (FP), are seen ahead of the flashing dots when the latter are flashed in perfect alignment with the former set of dots.

According to these authors, "... the visual system uses velocity information from motion detectors to compensate for spatial lag due to time lag, in identifying the instantaneous position of a moving object".

The extrapolation hypothesis was first questioned by Baldo and Klein (1995), who showed that the magnitude of the flash-lag effect was dependent on the visual eccentricity of the flashing stimulus (or its separation from the moving stimulus). According to the extrapolation hypothesis, the effect would depend solely on the kinematics of the moving stimulus, and should not depend on either the visual eccentricity of the flashing stimulus or its distance from the moving stimulus. Baldo and Klein (1995) have thus interpreted this perceptual phenomenon as resulting from a differential time delay between flashing and moving stimuli, relying on shifts of visual attention from the flashed to the moving stimuli. However, they also considered the possibility that "purely sensorial mechanisms, operating preattentively and depending on eccentricity" might contribute to the flash-lag effect as well (Baldo and Klein 1995). More recently, the sensory component of the flash-lag effect has been examined by other authors (Lappe and Krekelberg 1998; Purushothaman et al 1998; Whitney and Murakami 1998). Purushothaman et al (1998) and also Lappe and Krekelberg (1998) have shown that the magnitude of the flash-lag effect varies according to the luminance of the flashed and moving stimuli. Their results showed that the extrapolation mechanism does not compensate for luminance-dependent variations in visual latency. To further test the extrapolation model, the perceptual relative position between moving and static stimuli has been investigated under the abrupt disappearance of the moving stimulus (Baldo et al 1997; Whitney et al 2000) and its sudden reversal of motion (Whitney and Murakami 1998; Whitney et al 2000). Whereas the extrapolation model predicts that the moving stimulus would continue being extrapolated forward along its path, eventually overshooting the disappearance or reversal point, no perceptual overshoot at all has been observed by these authors.

A more trivial explanation for the flash-lag effect would be a differential visible persistence of flashed and moving stimuli. If the offset of the flashed stimulus, instead of its onset, had been used by observers as the temporal marker signaling the moment of the alignment judgment, a shorter visible persistence of the moving stimulus, possibly due to deblurring mechanisms (Burr 1980; Burr and Morgan 1997), might result in the perception of a flash lagging behind the moving stimulus (conversely, the moving stimulus would be perceived as leading the flashing stimulus). This possibility was previously investigated either by simply removing the offset phase of the static stimulus (Namba et al 1998) or by masking the flashed stimulus (Whitney et al 2000). In neither approach were the results consistent with a persistence model.

The possible role of attentional mechanisms in determining differential latencies for moving and flashing stimuli was first proposed in view of the dependence of the flash-lag effect on the eccentricity of flashing stimuli (Baldo and Klein 1995). We found that the magnitude of the flash-lag effect was significantly dependent upon the location of the flashing stimulus, presented at two eccentricities randomly chosen from trial to trial. According to our previous attentional model (Baldo and Klein 1995), the time needed to shift visual attention from the flashing to the moving dot would be proportional to the distance between them (Tsal 1983; Weichselgartner and Sperling 1987; Kröse and Julesz 1989; Saarinen and Julesz 1991). This simple model might explain not only the flash-lag effect itself, but its dependence on the separation between moving and flashing stimuli as well. However, this interpretation was only tentative about possible mechanisms of attentional deployment, lacking persuasive empirical evidence for the participation of attentional factors in the flash-lag phenomenon. Besides, the role of eccentricity in modulating the flash-lag effect is unavoidably coupled to its primary influence on sensory processing. A conclusive participation of attention in the flash-lag would thus require uncoupling the attentional manipulation from eccentricity influences.

Our purpose in the present work was twofold. First, we aimed to assemble evidence showing the inappropriateness of both visible-persistence and motion-extrapolation models as explanations for the flash-lag phenomenon (experiment 1). As a second goal, we attempted to demonstrate convincingly the role of attentional mechanisms in determining the differential latencies responsible for this perceptual phenomenon (experiment 2).

2 Experiment 1

Experiment 1 comprises four conditions of stimulation. Condition 1 replicates our previous findings (Baldo and Klein 1995), reproducing the standard flash-lag effect, and serves as a baseline for further comparisons across the four experimental conditions. Conditions 2 and 3 tested whether a differential visible persistence could explain the flash-lag effect. Condition 4 was set to address a direct prediction of the motion-extrapolation hypothesis. According to the extrapolation hypothesis, a moving stimulus suddenly disappearing from the visual field should be perceived as leading the location of its physical disappearance.

2.1 *Methods*

2.1.1 *Stimuli and apparatus.* The stimulus (figure 2a) was a pair of dots, 2 deg apart in the visual field, rotating clockwise at 36 rev. min^{-1} about the fixation point (FP). Another pair of dots (outer dots), diametrically opposed to each other and aligned to the FP, was presented randomly either at 1.7 or 3.9 deg of visual eccentricity. The rotating and outer dots subtended 0.11 and 0.23 deg of the visual field, respectively. The luminance of all dots was 21.4 cd m^{-2}, displayed on a dark background. Stimuli were generated on a 486-based PC and rendered on a Sony Multiscan 15 sf II monitor with a 60 Hz vertical refresh rate. A chin-rest was used to maintain a constant viewing distance of 50 cm, and the experiments were conducted in a dimly lit room. Participants used the dominant eye, with the contralateral eye occluded by an eye-patch. Eye movements were monitored by a video camera.

2.1.2 *Design and procedure.* After initiating a trial by pressing a key on the keyboard, participants fixated on the FP (center of the display), and the moving dots started rotating about the FP. The whole experiment was composed of four blocked conditions in which the design differed only with regard to the visual event that served as the

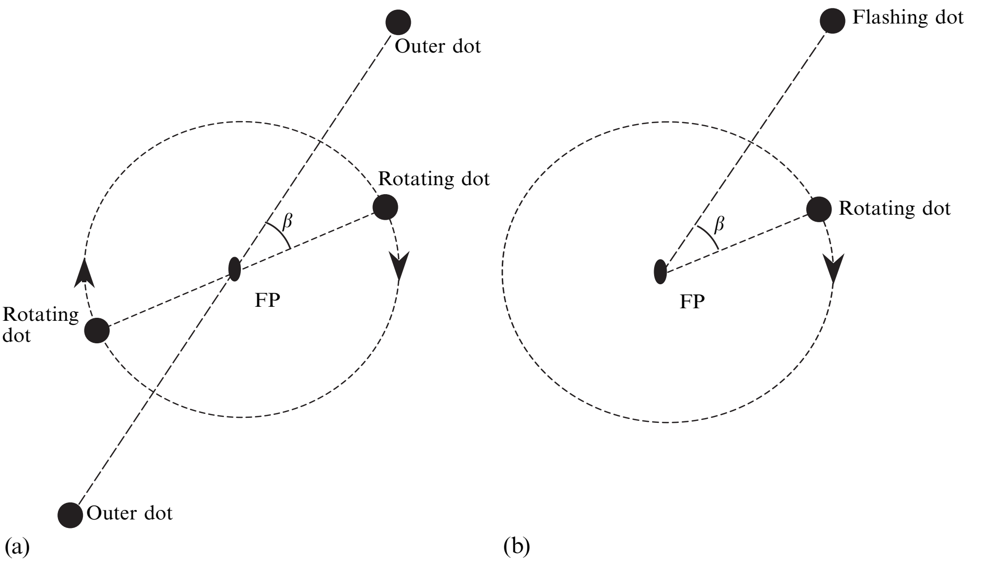

Figure 2. Visual stimuli used in experiments 1 and 2. (a) In experiment 1, two rotating dots 2 deg apart in the visual field, diametrically opposed to each other, rotate clockwise at 36 rev. min^{-1} about the fixation point (FP). The observer's task was to report the perceived angle β as a lead ($\beta > 0$) or a lag ($\beta < 0$) of the rotating dots in relation to the outer dots at the moment a temporal marker was presented in the visual field (see figure 3). (b) A similar stimulus was used in experiment 2, the only difference being the presentation of only one rotating dot and only one outer dot.

temporal marker prompting the alignment judgment [Khurana and Nijhawan (1995) were the first authors to manipulate the timing between the abrupt (flash) and continuous (moving) stimuli, in order to explore the flash-lag effect]. After two or three revolutions of the rotating dots, when they were in the vicinity of the imaginary line connecting the outer dots and the FP, the specific temporal marker was presented. The abrupt visual events that served as temporal markers were designed in the following way (figure 3):

Condition 1: the outer dots were flashed (*onset – offset condition*) in the visual field during one frame (16.7 ms).

Condition 2: the outer dots were presented as a luminance step-function (*onset condition*), remaining on the screen after their onset until the whole set of dots was removed from the display.

Condition 3: the outer dots were presented on the screen since the moving dots started rotating about the FP, and were suddenly turned off (*offset condition*).

Condition 4: the outer dots remained on the screen during the entire stimulus presentation, providing only a spatial reference; after two or three revolutions about the FP, the pair of rotating dots was suddenly turned off (*moving offset condition*).

The location of the rotating dots at the moment marked by the abrupt visual event was randomly chosen, trial by trial, from 11 equally spaced positions (method of constant stimuli). At these positions, the misalignment angle between the imaginary lines connecting the FP to the rotating and outer dots ranged from $-36°$ (-167 ms) to $+36°$ ($+167$ ms), $0°$ (0 ms) indicating a perfect alignment between the outer and the rotating dots (figure 2a). The task in all four conditions was to judge the location of the rotating dots in relation to the imaginary line connecting the outer dots and the FP, at the moment indicated by the temporal marker. By pressing one of two designated keys on the computer keyboard, this judgment was reported as a lag or a lead of the rotating dots in relation to the outer dots, corresponding to negative or positive angles between those imaginary lines, respectively [we occasionally refer to the *flash-lag* effect

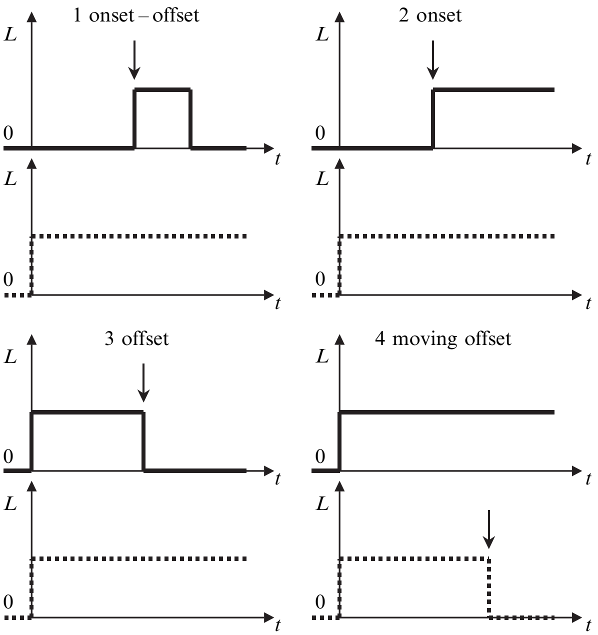

Figure 3. Time course of the luminance, L, of rotating (dashed lines) and outer (solid lines) dots, as a function of time, t, in conditions 1 to 4 of experiment 1. The judgment of the position of the rotating dots in relation to the outer dots (leading or lagging) was made at the moment at which the temporal marker, indicated by the arrow, occurred in the visual field.

as the *lead* of the *rotating dots* in relation to the static (outer) dots]. The next trial was started immediately after a response key had been pressed.

The complete experimental series, comprising eight daily sessions (two sessions for each condition), was run on different days, each participant being submitted twice to each condition for training purposes (the first data set collected in each experimental condition was discarded from the data analysis). The sequence of conditions was randomized for each participant. Each experimental session lasted approximately 45 min, comprising 200 trials divided into four blocks.

2.1.3 *Participants.* Eight students from the University of São Paulo, naïve with respect to the particular hypothesis being tested, and two of the authors participated as volunteers in all four experimental conditions. All participants, aged between 20 and 36 years, had normal or corrected-to-normal vision.

2.1.4 *Data analysis.* Eight psychometric curves were obtained from each participant (4 temporal-marker conditions $\times$ 2 eccentricities for the outer dots). Data points in each empirical psychometric curve were approximated by a cumulative Gaussian function, and the point of subjective equality (PSE) was determined as the horizontal position of the psychometric function measured by the vertical location of the 50% point. The calculated PSE corresponds to the angle, converted to milliseconds, needed to generate a perception of alignment between moving and outer dots, and is expressed as the negative of the perceived angle. Therefore, negative (positive) values mean a perceptual lead (lag) of the moving dots in relation to the outer dots.

The PSE values were computed for every participant and each condition separately. The results of the experimental conditions were entered into a 4×2 repeated-measures analysis of variance (ANOVA) with factors Condition and Eccentricity, followed by pairwise comparisons (Tukey's HSD test). The significant level was set at 5%.

2.2 *Results and preliminary discussion*

Figure 4 shows the mean PSE obtained in all four conditions of experiment 1, for both eccentricities of the outer dots. A two-way repeated-measures ANOVA showed a significant main effect for both factors: Condition ($F_{3,27} = 53.1$, $p < 0.001$) and Eccentricity ($F_{1,9} = 13.3$, $p = 0.005$); a significant interaction between these two factors was detected as well ($F_{3,27} = 8.9$, $p < 0.001$).

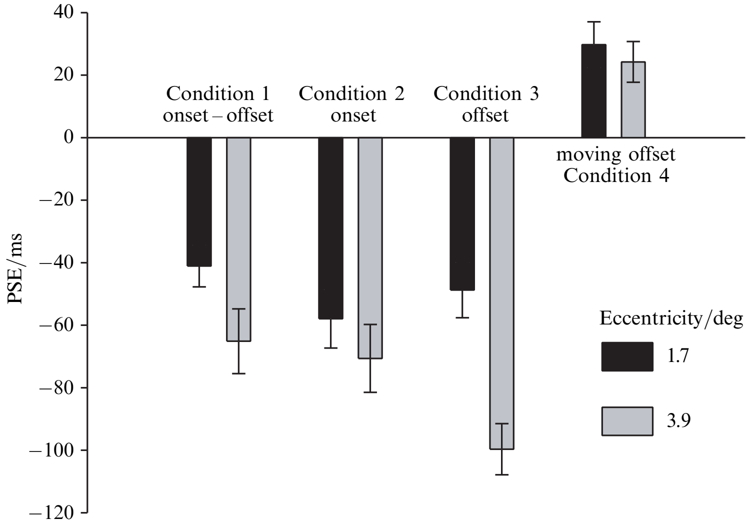

Figure 4. Point of subject equality (PSE) obtained in experiment 1 (error bars represent SEM). The PSE values are expressed in milliseconds (by dividing the misalignment angles by the angular velocity of the rotating dots) as a function of both the temporal marker (conditions 1 to 4) and the visual eccentricity of the outer dots. Negative values for the PSE mean that the rotating dots had to be lagging the outer dots in order to be perceived as aligned with them, ie the rotating dots were perceived as leading the outer dots when the temporal marker happened to indicate a perfect alignment of the two sets of dots. The opposite holds for positive values for the PSE.

In condition 1 (onset – offset), a significant difference was found between the eccentricities of the two outer dots ($p = 0.020$), confirming our previous findings concerning the dependence of the flash-lag effect on the location of the flashed stimulus (Baldo and Klein 1995).

Comparing conditions 1 and 2, we found no significant difference between the perceptual effects for either eccentricity ($p = 0.209$ and $p = 0.988$ for 1.7 deg and 3.9 deg, respectively). Since in condition 2 the outer dots had an extended presentation (onset condition) without the offset phase present in condition 1 (onset – offset condition), we are led to the conclusion that observers have not been using the offset of the flashing (outer) dots as the temporal marker for the alignment judgment. Moreover, when the only temporal marker available was the offset of the outer dots (condition 3), the magnitude of the flash-lag effect for the eccentricity of 3.9 deg was significantly greater than in any other previous condition ($p < 0.003$). Therefore, when the visual stimulus was set up in such a way to reveal the role of visible persistence (condition 3), the magnitude of the flash-lag increased significantly beyond the basal values found either in the onset – offset (condition 1) or the onset (condition 2) conditions. These results rule out the explanation of the original flash-lag phenomenon solely on basis of a differential visible persistence between flashed and moving stimuli. Besides, they provide a further evidence of the dependence of the perceptual effect not only on the characteristics of the moving stimuli but also on the visual features of the outer dots.

The mean PSE turned out to be positive in condition 4 (moving offset), and no significant difference was found for the eccentricities of the two outer dots in this condition ($p = 0.989$). According to the convention adopted, a positive PSE means that the moving dots had to be located ahead of the imaginary line connecting the outer dots in order to be perceived aligned with them. In other words, a positive PSE means that the moving dots were seen as lagging (behind) the location they actually disappeared. This result is in disagreement with the predictions of the extrapolation hypothesis. According to this hypothesis, a moving object should be seen ahead of its disappearance position because the perceptual and physical locations were already coincident at the disappearance moment (the very core of the extrapolation hypothesis). However, because some amount of time is required to perceive the disappearing event, the extrapolation process would go on, lengthening the object trajectory ahead of the disappearance point. Condition 4, therefore, contradicts a straightforward prediction of the extrapolation mechanism, supplying an empirical refutation of this hypothesis. The result of condition 4, being completely distinct from the flash-lag effect (which we explain by means of a *temporal* model), is in agreement with a *spatial* model in which the perceived position of a moving object is determined by an average of the signals of the object position (Lappe and Krekelberg 1998; Krekelberg and Lappe 2000). According to this spatial model, because the moving dots never move beyond their disappearance positions, they are, on average, behind them.

3 Experiment 2

Here we attempted to reveal the dependence of the flash-lag effect on the spatial predictability of the outer dots, uncoupling the potential influence of attention from stimulus eccentricity. Comparing two experimental conditions differing only with respect to the predictability of the location of the outer dots, we might infer that any observed difference in the magnitude of the flash-lag effect would rely on attentional mechanisms, since both conditions are similar to each other with respect to any other sensory characteristic. Benefits of advance information about stimuli have often been termed *perceptual-set effects* (Pashler 1998). As a particular instance of perceptual-set manipulations, since we are comparing the outcome of procedures in which predictability was kept either high or low, experiment 2 can be conceived of as measuring *uncertainty effects.*

3.1 *Methods*

3.1.1 *Stimuli and apparatus.* The experimental apparatus and visual stimulation were identical to those employed in experiment 1. The only difference was the use of only one moving dot rotating about the fixation point, at an eccentricity of 1 deg, and only one outer dot, presented at an eccentricity of either 1.7 deg or 3.9 deg (figure 2b). The reason for this choice was to minimize the presence of distractors, allowing the allocation of a narrower focus of visual attention to the appropriate targets.

3.1.2 *Design and procedure.* The procedure was similar to that used in experiment 1. The temporal marker prompting the alignment judgment was a flash of the outer dot for 16.7 ms (onset – offset profile). Experiment 2 comprised two conditions. In a blocked condition, the flashing dot was presented at a fixed, highly predictable, eccentricity (1.7 deg or 3.9 deg, depending on the experimental block), thus allowing previous allocation of visual attention. In a randomized condition, the eccentricity of the flashing dot was randomly chosen from the two possibilities (1.7 deg or 3.9 deg) at each presentation, thus precluding previous allocation of a narrower focus of visual attention to those particular positions.

3.1.3 *Participants.* Nine naïve observers plus one author (aged 20 – 31 years) participated as volunteers in all experimental conditions. All participants had normal or corrected-to-normal vision.

3.1.4 *Data analysis.* Four data sets were obtained from each participant (2 predictability conditions $\times$ 2 eccentricities for the flashing dot). The conventions and analytical procedures were the same as in experiment 1.

3.2 *Results and preliminary discussion*
Figure 5 shows the mean perceptual lead of the rotating dot for both conditions: eccentricity (1.7 deg and 3.9 deg) and predictability (high and low). A two-way repeated-measures ANOVA revealed a main effect for both factors, Predictability ($F_{1,9} = 10.06$, $p = 0.011$) and Eccentricity ($F_{1,9} = 14.51$, $p = 0.004$). A significant interaction between these factors was also observed ($F_{1,9} = 9.73$, $p = 0.012$). Increasing the eccentricity of the flashed dot increased the perceptual lead, as already observed in experiment 1. Decreasing the predictability of the flashing dot increased the perceptual lead from 12 ± 4 to 22 ± 7 ms (for an eccentricity of 1.7 deg) and from 32 ± 7 to 60 ± 12 ms (for an eccentricity of 3.9 deg). Both conditions (high and low predictability) were comparable to each other regarding their sensory characteristics, differing only by the possibility of previous allocation of larger amounts of attentional resources to the high-predictability location. Similar results showing the role of predictability in the flash-lag effect have been previously reported (Baldo et al 2000; Eagleman and Sejnowski 2000b).

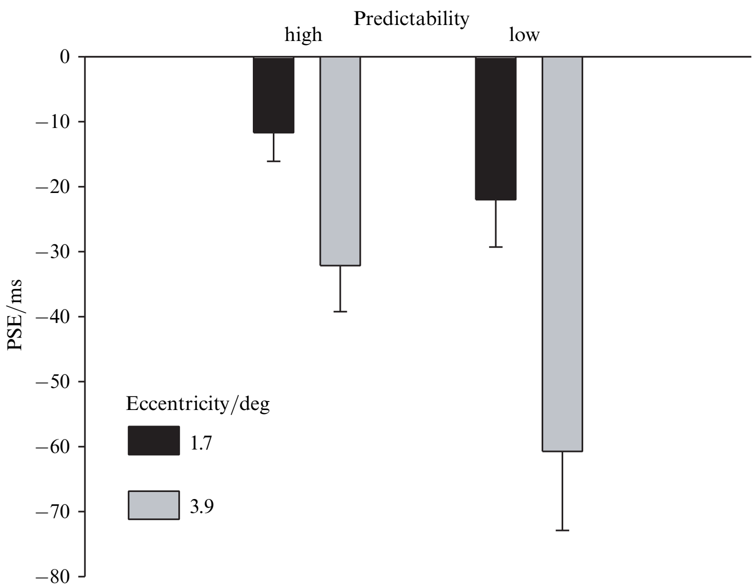

Figure 5. Point of subject equality (PSE) obtained in experiment 2 (error bars represent SEM) as a function of both factors: Predictability and Eccentricity of the flashing (outer) dot. The conventions are the same as those adopted in figure 4.

These results support our proposition, according to which attentional delays contribute to perceptual latencies. A higher location predictability of the flashing dot allowed attention to become more narrowly allocated, leading to greater focalization of attentional resources on the expected location of the stimulus appearance. Therefore, by comparing the two predictability conditions, it was possible to uncouple the attentional influence from sensory effects brought about by the stimulus eccentricity. Furthermore, it was possible to measure the individual contribution of focused attention to the overall latencies, estimated as 10 ± 5 ms at 1.7 deg and 28 ± 8 ms at 3.9 deg.

These figures were calculated by subtracting, for each eccentricity separately, the perceptual lead obtained in the high-predictability condition from that obtained in the low-predictability condition.

The dependence of the flash-lag effect on the spatial predictability of the flashing dot supports the idea that the perceptual latency, considered as the cause of this psychophysical effect, should be seen as a two-component process, in which attentional mechanisms could be responsible for as much as one half of the overall delays.

4 General discussion

A moving object is usually misperceived as spatially leading a flashed stimulus aligned with it (flash-lag effect). Over the past seven years, the perceptual mechanism underlying the flash-lag effect has received several nominees, including motion extrapolation (Nijhawan 1994), differential latencies (Lappe and Krekelberg 1998; Purushothaman et al 1998; Whitney and Murakami 1998), attentional set (Baldo and Klein 1995; Baldo et al 2000), and postdiction (Eagleman and Sejnowski 2000a). In the series of experiments reported here, we attempted to show that empirical evidence cannot sustain the accounts based either on visible-persistence mechanism or on the motion-extrapolation hypothesis. Whereas there might be other viable frameworks accounting for the flash-lag effect (Nijhawan 1994; Krekelberg and Lappe 1999, 2000; Eagleman and Sejnowski 2000a, 2000b; Sheth et al 2000; Krekelberg 2001), we also attempted to demonstrate the participation of an attentional component contributing to the differential visual latency between moving and flashed stimuli.

4.1 *Differential visible persistence*

Visible persistence refers to the fact that a briefly presented visual stimulus appears to be visible for some time after its offset (Coltheart 1980; Long 1980, 1985). The visible persistence of an object in real or stroboscopic motion can lead to the perception of smearing or multiplicity of the visual object, respectively (Allen 1926; Allport 1968). Therefore, any visual process implementing a motion-deblurring mechanism could lead to a different amount of visible persistence between moving and static stimuli (Burr 1980; Burr and Morgan 1997; Kirschfeld and Kammer 1999). Considering a longer persistence of the flashing (static) stimulus in comparison to the moving (deblurred) stimulus, the flash-lag effect might be trivially explained by a differential visible persistence.

If the offset of the flashing stimulus were the time marker used by observers during the alignment judgments, removing the offset phase of the flashing stimulus should produce a significant effect on the magnitude of the flash-lag effect. However, conditions 1 (onset – offset) and 2 (onset) of experiment 1 did not significantly differ from each other, showing that the onset condition for the outer dots (lacking an offset phase) yielded a flash-lag effect similar to that generated by the onset – offset condition. Moreover, when the only time marker available was the offset of the outer dots (condition 3), the contribution of a longer visible persistence of the static (outer) dots to the overall effect could be revealed. We may thus conclude that the original flash-lag effect, where the moving stimulus is misperceived as leading a flashed stimulus, cannot be accounted for by a differential visible-persistence mechanism.

4.2 *Motion extrapolation*

A 100 ms delay in visual processing can be crucial for motor behaviors, such as hitting or catching a ball, or skipping a colliding object. During this time, an object travelling at 35 km h^{-1} covers about 1 m. It seems clear that efficient interceptive actions need to be compensated for delays in sensory perception, and there is evidence that anticipation of moving stimuli could start being accomplished as early as in the retinal processing (Berry et al 1999). Nonetheless, efficient motor behaviors are generated despite processing delays inherent not only to sensory pathways, but also to stages involved in planning and executing the motor action, including the neuromuscular apparatus. Therefore, we should keep in mind that even an ideal perceptual extrapolation of the location of a fast-moving object would correct the afferent information only, leaving untouched the delays inherent to the motor pathways, consequently not assuring an appropriate efferent action.

Nijhawan (1994) suggested that such an extrapolation mechanism of moving objects might explain the flash-lag effect. The predictability of a moving stimulus would allow an early visual mechanism to correct the spatial lag by extrapolating instantaneous location of the moving object. Owing to the unpredictability of the flashed stimulus, the visual system could not overcome the transmission delay inherent to its processing, and a discrepancy between the perceptual location of moving and flashed stimuli would arise. The first empirical evidence against this hypothesis came from the observed dependence of the magnitude of the flash-lag effect on the eccentricity of the flashing stimuli (Baldo and Klein 1995). Condition 1 of experiment 1 replicates these previous findings, showing a statistically significant effect brought about by the eccentricity of the outer (flashing) dots. This dependence is not accounted for by the extrapolation hypothesis, which specifically relies on the characteristics of the moving stimulus.

Condition 4 of experiment 1 addressed a straightforward prediction of the extrapolation hypothesis, namely that a moving object would be perceived as disappearing *beyond (leading)* its actual disappearance point. Our results showed, on the contrary, that observers perceived the moving dot as disappearing *behind (lagging)* the virtual line connecting the fixation point and the outer dots. Similar results were previously reported by us (Baldo et al 1997) and more recently by Whitney et al (2000). These findings can be explained by means of a model put forward by Krekelberg and Lappe (1999, 2000), proposing that the perceived position of a moving object be based on an averaging process. According to these authors, the perceptual distance between objects is based on a long-time-scale average of differences in position signals. The effect obtained in condition 4 is in agreement with this averaging hypothesis since, on average, the moving stimulus was lagging the disappearance position.

The results observed in condition 4 are at odds with the notion of a representational momentum (Freyd 1987; Freyd and Johnson 1987), in which the remembered position of a moving target is shifted forward in the direction of motion. However, it has been recently shown that the characteristic time course of representational momentum is not observed with linear target motion (Kerzel 2000). Moreover, it was found that when observers maintained visual fixation during the task, no perceptual shift of the moving stimulus occurred at all on disappearing from the visual field (Kerzel 2000). As pointed out also by Kerzel (2000), these discrepancies might arise from both theoretical and methodological reasons. The former would involve differential memory mechanisms concerning real and implied motion. The latter would be related to the crucial role of visual fixation on determining the perceptual outcome.

4.3 *Differential latencies*

In the visual system, latencies arise from early stages of neural processing in the retina, and increase as the information is further transmitted to, and processed by, higher centers along the visual pathways. It is a well-established fact that processing speed for visual targets is dependent on their luminance (Cattell 1886; Roufs 1963; Wilson and Anstis 1969). Lappe and Krekelberg (1998) and also Purushothaman and colleagues (1998) showed that a motion-extrapolation mechanism does not adequately compensate for variations in visual latency controlled by varying the luminance of either the moving or the flashed stimulus. These findings led to the idea that the flash-lag phenomenon is the result of a differential visual latency between moving and flashed stimuli (Purushothaman et al 1998; Whitney and Murakami 1998). Yet, there is a vast literature reporting that observers can process visual inputs more effectively when they have prior information where the target is likely to occur (Pashler 1998).

We propose that besides several sensory factors, such as stimulus luminance and eccentricity, the observer's attentional set modulates the magnitude of the differential latencies that give rise to the flash-lag phenomenon. It is important to emphasize that our present conceptual framework in explaining the flash-lag effect proposes a *generalized latency model*, composed of intrinsic sensory delays and of a modulatory component conveyed by the attentional set. Therefore, the essential presence of differential sensory delays explains the persistence of the flash-lag effect when attentional influences are minimized or even removed, as previously reported (Khurana and Nijhawan 1995; Khurana et al 2000). One could argue that these latency factors (arising from both sensory and attentional sources) could be superposed on another underlying factor, such as motion extrapolation. However, the refutation of motion extrapolation as a likely model arises not from the mere demonstration of luminance or attentional influences on the flash-lag effect, but mainly from the fact that straightforward predictions of the flash-lag model are empirically disproved, as reported here (experiment 1, conditions 1 and 4) and elsewhere (Baldo et al 1997; Whitney and Murakami 1998; Brenner and Smeets 2000). Also, since a generalized latency model is able to assimilate the current evidences concerning the flash-lag effect, it is reasonable to retain the smallest and simplest conceptual model.

4.4 *Attentional set*

Apart from the influence of the physical attributes of the stimulus, perceptual latencies have also been shown to be modulated by the differential allocation of attention (Posner 1978, 1980; Posner et al 1980). When attention has not been shifted to the target prior to its appearance, additional processing time would be required, either for the attentional shift to be completed, or because the target must be processed with reduced attentional facilitation. Either of these alternatives is sufficient to result in a longer detection time of the flashing (outer) dot in the low-predictability condition in comparison to the high-predictability condition, as reported here (experiment 2). A longer detection time (longer latency) of the flashing dot would accordingly result in a greater magnitude of the flash-lag effect, as indeed observed.

Even though our first account of the flash-lag effect relied on shifts of attention across the visual field (Baldo and Klein 1995), movements of the attentional focus, as portrayed by the spotlight metaphor (Tsal 1983; Weichselgartner and Sperling 1987; Kröse and Julesz 1989; Saarinen and Julesz 1991), are not essential to our proposal. Our fundamental claim is that the attentional set contributes to perceptual latencies, in accord with a generalized latency model, correspondingly modulating the flash-lag effect. The participation of attention in the flash-lag phenomenon therefore does not discriminate or elect a specific model of visual attention.

As an example, it is worth noting that a gradient-zoom-lens model for attention (LaBerge 1983; Eriksen and St James 1986; Eriksen and Murphy 1987; Barriopedro and Botella 1998) might also easily explain our findings (figure 6): in the high-predictability condition, the focus of attention would be distributed around the (predictable) location of the flashing dot, speeding up its detection and decreasing the flash-lag effect; in the condition of low predictability, the attentional focus could presumably be distributed either around the fixation point or in the vicinity of the trajectory of the moving dot, with the attentional facilitation monotonically decreasing toward the periphery of the visual field. This model helps explain the increase of the flash-lag effect with decreasing predictability. Also, it might explain the stronger dependence of the effect on the visual eccentricity for the lower-predictability condition, as compared to the higher-predictability condition (which led to a significant interaction between these

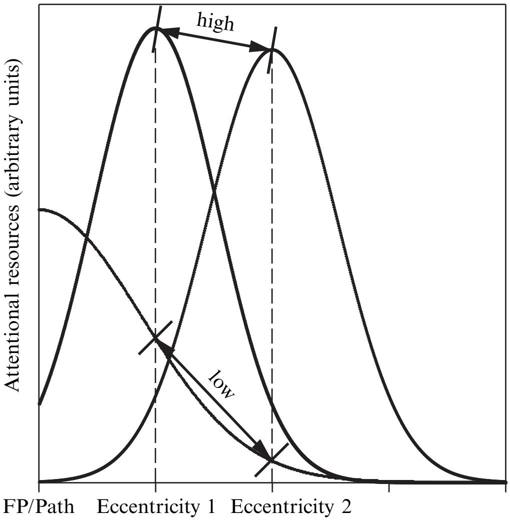

Figure 6. Hypothetical distribution of attentional resources, according to a *zoom-lens* model, in two predictability conditions for the location of the outer dot. Under high predictability, a narrower and more efficient attentional focus can be distributed around the location of the outer dot, predictably presented at one of two eccentricities. On the other hand, if the location of the outer dot is randomly chosen from both eccentricities (low predictability), a wider and consequently less efficient focus of attention might be distributed around the fixation point (FP) or, alternatively, in the vicinity of the trajectory of the rotating dot (Path). For each eccentricity separately, the bell-shaped curves make clear the difference between the amounts of attentional resource available under conditions of high and low predictability. Conversely, when analyzing each predictability condition separately (high or low), the arrows indicate the decay in attentional resources with the increase in outer dot eccentricity. The model helps explain not only the greater efficiency in processing the flashing dot in the condition of higher predictability but also its steeper decay with increasing eccentricity in the condition of lower predictability.

factors). In short, the zoom-lens model for visual attention is able to assimilate the effect of predictability as well as the effect of eccentricity on the flash-lag phenomenon.

Recently, Beena Khurana and colleagues (Khurana et al 2000) have carried out a series of experiments that seem to rule out the participation of attention in the flash-lag effect, apparently lending support to the original extrapolation hypothesis. By manipulating the voluntary allocation of visual attention in a series of experiments, they obtained a significant and unchanging flash-lag effect under all attentional conditions employed. Their main conclusion was that the mechanisms that originate the flash-lag effect are independent of attentional deployment. Despite the elegance of those experiments in manipulating the deployment of visual attention (Khurana et al 2000), some inadequacies regarding the experimental design and data analysis might have spoiled their main conclusions. Because of these inadequacies (statistical analysis not suitable to categorical data, pseudoreplication, low statistical power, and the use of a stimulus onset asynchrony inappropriately short for cueing the deployment of voluntary attention), their conclusion that the flash-lag effect is not affected by attentional deployment seems to be unwarranted on the basis of the presented data.

A more important issue is that we argue that attention participates in the flash-lag modulation as a factor belonging to a generalized latency model. In this sense, the perception of moving and abrupt-onset stimuli would have different temporal dynamics, owing to differences in neural mechanisms that may range from sensory processing in retina to higher stages of perceptual processing, including the deployment of attention. Therefore, we allege that the flash-lag effect would not be *caused* by attentional mechanisms but rather *modulated* by them. The main consequence of this concept is that, contrary to the claim by Khurana and colleagues (Khurana and Nijhawan 1995; Khurana et al 2000), the flash-lag effect should not disappear even in a condition where attention is voluntarily and effectively focused on the visual target.

5 Conclusions

According to the results of experiment 1 in the present study, the magnitude of the flash-lag effect remains unchanged when the offset phase of the flashing stimulus is removed, suggesting that the perceptual effect does not arise from a longer visible persistence of the flashing stimulus in comparison to the moving stimulus. The findings in experiment 1 also disproved a direct prediction of the motion-extrapolation hypothesis according to which a moving stimulus, suddenly disappearing from the visual field, would be perceived as leading the location of its disappearance. The refutation of visible persistence and motion extrapolation as appropriate explanations of the flash-lag phenomenon strengthens the belief that this perceptual effect arises from generalized differential latencies between flashing and moving stimuli. The results of experiment 2 clearly indicate that the magnitude of the flash-lag effect is dependent upon the predictability of the location of the flashing dot. This dependence strongly suggests that the attentional set modulates the extent in which differential visual latencies determine the flash-lag phenomenon.

In conclusion, a generalized latency model, bearing a fundamental sensory element and a modulatory attentional component, would be able to explain most of the empirical data concerning the flash-lag effect reported so far.

Acknowledgements. We thank Ronald Ranvaud, Luiz Ribeiro-do-Valle, and Odival Gasparotto for useful suggestions; Roberto Vieira for technical assistance; and two anonymous reviewers for valuable comments. This research was supported by FAPESP (Brazil), grant 96/6618-9 and fellowships 96/06619-5 and 96/11853-7. Preliminary reports of this work were presented at the 27th and 28th Society for Neuroscience Annual Meetings (New Orleans 1997 and Los Angeles 1998, respectively), and at the Association for Research in Vision and Ophthalmology Annual Meeting (Fort Lauderdale 2000).

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