Interpolation of the past: Can a postdictive framework for visual awareness explain the flash-lag illusion?

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Abstract

The flash-lag effect is a visual illusion in which a continuously moving object and a briefly flashed object are perceived to be spatially offset. Despite being perfectly aligned, the flashed object appears to lag the moving object. Following the rediscovery of the flash-lag effect by Nijhawan in 1994, various researchers have challenged Nijhawan's original interpretation of the effect and offered alternative accounts. Here, I focus on describing the 'postdictive' framework for visual awareness introduced by Eagleman and Sejnowski in 2000, and I will elaborate on the debate that followed soon after the model was proposed. In particular, I elaborate on the different models each group of researchers advocates and I highlight specific points of disagreement.

Keywords: flash-lag illusion, Fröhlich effect, motion extrapolation, differential latency, temporal integration, postdiction

Introduction

When a stationary stimulus is briefly flashed in alignment with a moving stimulus, the flashed object is usually perceived to lag the moving object spatially (see Fig. 1, for more). This effect is commonly referred to as the *flash-lag effect* (FLE) and was first reported by Metzger (1932) in his work on two perceptual effects related to the FLE that had previously been observed (Fröhlich,

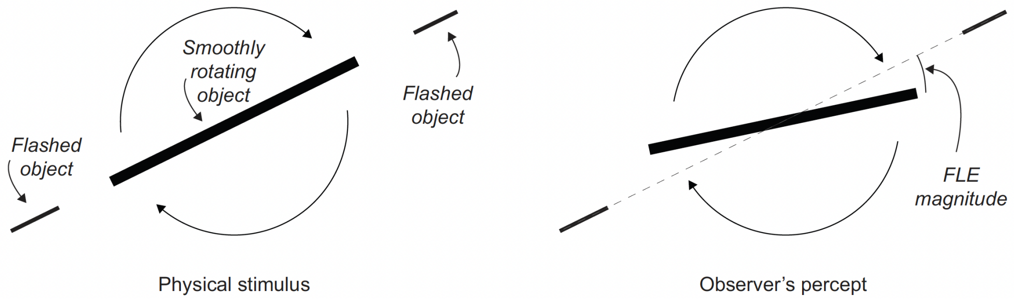

Figure 1. Setup presented by Nijhawan (1994) that causes the flash-lag illusion. *Left*, the stimulus that is presented. A line segment is rotating clockwise around a fixed centre of rotation. The central segment is continuously visible while the two outer segments are only briefly flashed. *Right*, the perceived illusion. The flashed segments of the line appear to spatially lag behind. The magnitude of the effect (i.e., the angular displacement) tends to increase with the angular velocity of the line segment (Nijhawan, 1994).

Note. From "Motion Extrapolation in Visual Processing: Lessons from 25 Years of Flash-Lag Debate," by H. Hogendoorn, 2020, *Journal of Neuroscience, 40*(30), p. 5699 (https://doi.org/10.1523/JNEUROSCI.0275-20.2020). Copyright 2020 by Society for Neuroscience.

1923; Hazelhoff & Wiersma, 1924).

Independent of Metzger's work, a similar effect (stroboscopic illusion) was discovered again by MacKay (1958). However, it was not until a second rediscovery of the FLE by Nijhawan (1994) that the illusion and the study of its underlying perceptual mechanisms gained widespread interest among scientists (Hogendoorn, 2020). Following Nijhawan's rediscovery of the illusion, many authors have proposed their own accounts of the mechanisms underlying the FLE.

Since there already exists a large number of comprehensive reviews of these accounts (e.g., Hogendoorn, 2020; Hubbard, 2014; Nijhawan, 2008), I will not introduce all of them one by one. Instead, I will focus on the *postdictive framework* offered by Eagleman and Sejnowski (2000a) and the debate it caused among scientists. To do so, I will first introduce only those explanations of the FLE that are involved in the aforementioned debate. Then, I will elaborate on the postdictive model proposed by Eagleman and Sejnowski (2000a) and their attempts of disproving previously suggested (i.e., prior to their own work) explanations of the FLE. Afterwards, I will outline the debate that soon followed the proposal of the postdictive framework by Eagleman and Sejnowski. When doing so, I will pay considerable attention to specific points of disagreement between the debating groups of authors. Finally, I will conclude by presenting my own thoughts on the topic.

Proposed accounts of the FLE

Out of the multiple explanations of the FLE that different research groups have offered, three are particularly relevant to the debate that was sparked by the proposal of the postdictive framework by Eagleman and Sejnowski (2000a): motion extrapolation, differential latency and temporal integration. I will separately introduce all three of these theories.

Motion extrapolation. In his account of the flash-lag illusion, Nijhawan suggests that the visual system compensates for the delays inherent in processing visual information by extrapolating the location of a moving stimulus into the future based on its previous trajectory (Nijhawan, 1994; see also Khurana and Nijhawan, 1995; Nijhawan, 1997). This *latency correction via motion extrapolation* needs to rely on information prior to some point in time t to predict a moving object's location at t. Nijhawan argues that because the continuously visible line segment (Fig. 1) moves at a constant speed, its future location is highly predictable. In contrast, the positions of the flashed line segments are highly unpredictable. Hence, the visual system should be unable to overcome the processing delay for briefly flashed objects, resulting in a 'differential processing delay', and thus causing the illusory displacement of moving and flashed line segments (Nijhawan, 1994).

It should be pointed out that the differences in visual latency, as argued for by Nijhawan are *not* based on distinct processing speeds for moving and flashed objects *per se*. Instead, they result from the visual system's inability to overcome the visual latency for flashed objects due to their unpredictable nature.

Finally, it is worth mentioning that the average time delay of the flashed line segments (computed as angular displacement divided by angular velocity) observed by Nijhawan (1994) is about 82 ms.

Differential latency. A second explanation of the FLE multiple sets of authors have put forward is the *differential latency* model (e.g., Öğmen et al., 2004; Patel et al., 2000; Purushothaman et al., 1998; Whitney & Murakami, 1998; Whitney et al., 2000). Although the various models proposed by different groups of researchers naturally differ slightly, the key assumption of these models is the same: Visual latency depends directly on the properties of a stimulus, such as its luminance (Purushothaman et al., 1998), for

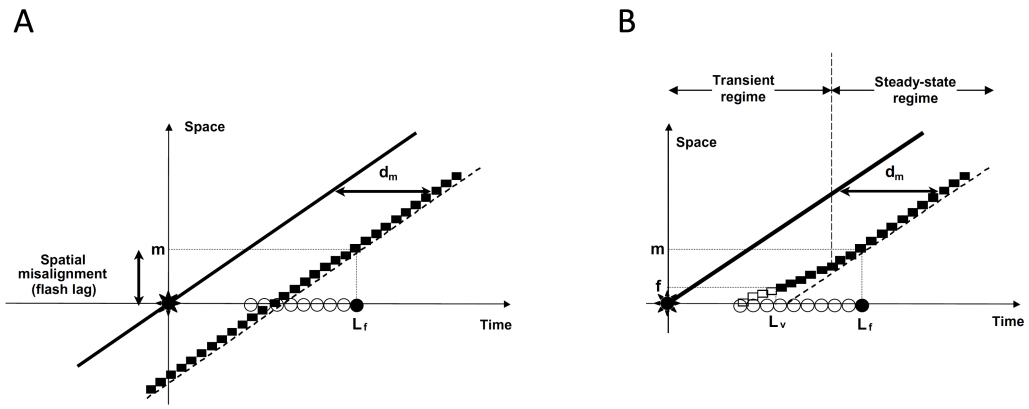

Figure 2. Differential latency model and the flash-lag effect. Computed positions of the flashed and moving stimuli are depicted by circles and squares, respectively. Filled markers represent computed locations that are perceived by an observer. *(A)* Continuous motion paradigm. The moving object's motion has started well before the flash is presented. *(B)* Flash-initiated cycle paradigm. Motion onset of the moving object and presentation of flash occur simultaneously.

Note. Adapted from "Differential latencies and the dynamics of the position computation process for moving targets, assessed with the flash-lag effect," by H. Ögmen, S. S. Patel, H. E. Badell and K. Camuz, 2004, *Vision Research, 44*(18), pp. 2111–2112, (https://doi.org/10.1016/j.visres.2004.04.003). Copyright 2004 by Elsevier Ltd.

example, thus causing slight delays for different stimuli to reach awareness if presented simultaneously.

Moving stimuli are often assumed to have shorter latencies compared to flashed stimuli (Whitney & Murakami, 1998) and are thus perceived to spatially lead the latter if presented concurrently at the same location, as is often reported in the flash-lag illusion. This general idea that flashed stimuli take longer to reach awareness had already been proposed by Metzger (1932). However, this need *not* always be the case: Purushothaman et al. (1998) have shown that, by increasing the luminance of the flashed segments (Fig. 1), they can be perceived to spatially *lead* the inner, continuously visible segments in the flash-lag illusion.

Another critical aspect of the differential latency model proposed by Öğmen et al. (2004) is the differentiation between the *continuous motion* (CM) paradigm and the *flash-initiated cycle* (FIC) paradigm. The two paradigms are illustrated in Figure 2. The key difference between these two paradigms is the point in time at which the moving object starts to move (in relation to the presentation of the flashed stimulus). Whether or not the moving object has begun to move *before* the flash is presented has an impact on the computational process that determines the moving object's location (again, in relation to the flashed object's position), as I will explain next.

In the CM paradigm, the moving object has started its motion long before the flash is presented. In this case, the computational process responsible for determining the moving object's location has reached a 'steady-state' and the perceived spatial misalignment of moving and flashed stimuli depends solely on the latency L_f of the flashed stimulus and the latency d_m of the moving object in the aforementioned steady-state (Öğmen et al., 2004). The magnitude m of the effect is given by $m = (L_f - d_m)s$, where s denotes the speed of the moving object. In this paradigm, the differential latency model predicts a flash-*lag* effect if the latency L_f of the flashed stimulus is larger than the latency d_m of the moving object. However, if the converse is true ($L_f < d_m$), the model predicts a flash-*lead* effect, as has been observed by Purushothaman et al. (1998).

On the other hand, in the FIC paradigm, the flash is presented simultaneously with the moving object's motion onset. Due to the time L_v it takes for the moving object to first become visible, the beginning portion of the moving object's trajectory is predicted not to be perceived by an observer; this phenomenon is the well-known Fröhlich effect (Fröhlich, 1923). The magnitude of this effect is depicted by f in Figure 2 B. If the duration L_v necessary for the moving object to be perceived initially is shorter than the latency L_f of the flashed object, the computation of the moving object's location is completed earlier than that of the flashed object. Additionally, at the instant that the flashed object is first perceived, the moving object is *always* predicted to spatially lead the flashed object if both are presented at the identical location.

Last, it should be mentioned that Nijhawan had already used both the CM paradigm as well as the FIC paradigm in his studies (Khurana & Nijhawan, 1995; Nijhawan, 1994) prior to the work of Öğmen et al. (2004).

Temporal integration. A third explanation of the FLE that has been proposed is that of *temporal integration* (Krekelberg & Lappe, 1999, 2000a, 2000b; Lappe & Krekelberg, 1998). According to this theory, the perceived position of moving and flashed objects results from an averaging process that extends over some time Δ, referred to as the *integration window*. Thus, according to the temporal integration hypothesis, the perceived trajectory of a moving object represents a (possibly weighted) moving aver-

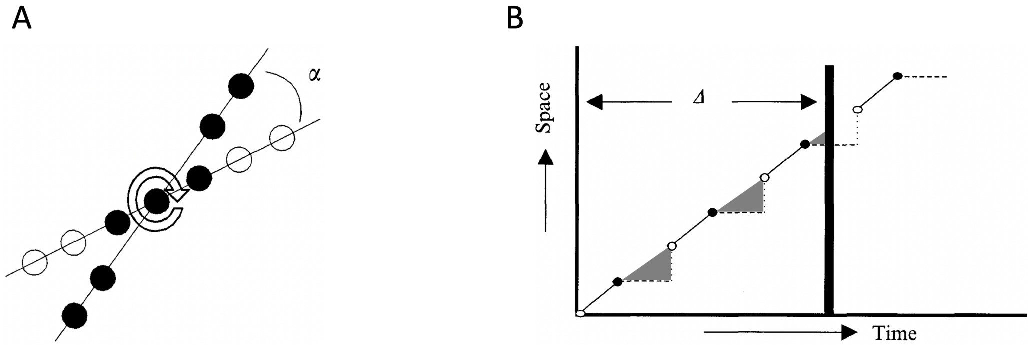

Figure 3. Flash-lag effect and temporal integration. *(A)* Experimental design of Lappe and Krekelberg (1998), adapted from an earlier experiment by Baldo and Klein (1995). *(B)* Space-time diagram illustrating the temporal integration model proposed by Lappe and Krekelberg.

Note. Adapted from "The position of moving objects," by M. Lappe and B. Krekelberg, 1998, *Perception, 27*(12), pp. 1439, 1447 (https://doi.org/10.1068/p271437). Copyright 1998 by SAGE Publications.

age of the physical trajectory that the object travels along.

The experimental design of Lappe and Krekelberg (1998) and a space-time diagram illustrating the temporal integration model are portrayed in Figure 3.

The stimulus consists of a total of seven dots rotating clockwise around a fixed centre (Fig. 3 A). Whereas the inner three dots are visible at all times, the two pairs of outer dots are only flashed briefly. Depicted by *unfilled* circles is the physical position of the dots; *filled* circles represent the observers' percept. The angle α denotes the magnitude of the FLE.

The temporal integration hypothesis is best illustrated by a space-time diagram (Fig. 3 B). The perceived position of both moving and flashed objects is the average of their respective positions over a time interval Δ prior to the moment of perception (bold vertical line in Fig. 3 B). Unfilled circles represent the time and location of the outer dots being turned on; filled circles depict the moment when they are turned off again. In the example shown in Figure 3 B, the outer dots are flashed three times prior to the moment of perception. Solid lines in between two circles portray the physical trajectory while the outer dots are visible. Once the outer dots are turned off, the last visible position is retained by the system (dashed horizontal lines in Fig. 3 B) and used to compute the positional average (Krekelberg & Lappe, 2000b). Consequently, the perceived displacement between flashed and moving dots at the moment of perception is given by "the average of the difference of the two position signals" (Krekelberg & Lappe, 2000b, p. 1107a) over the integration window, which equals the shaded area in Figure 3 B divided by Δ.

The temporal integration hypothesis correctly predicts the flash-lag illusion: Suppose the stimulus is set in motion, and the outer dots are briefly flashed only once. In that case, the positional average of the flashed outer dots equals their physical position. However, to compute the positional average of the continuously visible inner dots, the model considers a relatively large portion of the trajectory the inner dots travel along *after* the flash. Hence, the temporal integration model predicts the inner dots to be perceived to lead the flashed outer dots.

There are two more predictions the temporal integration hypothesis makes that are worth mentioning: First, the magnitude of the FLE should decrease as the trajectory of the flashed dots becomes visible to a greater extent (e.g., by flashing the outer dots more often or for longer periods of time). Second, the FLE should vanish altogether if the movement of the inner dots is stopped at times when the outer dots are turned off. Both of these predictions have been confirmed by experimental evidence (Eagleman & Sejnowski, 2000a; Krekelberg & Lappe, 1999, 2000a; Lappe & Krekelberg, 1998).

A postdictive framework

In their article "Motion Integration and Postdiction in Visual Awareness", Eagleman and Sejnowski (2000a) present a new framework for visual awareness, which they dub 'postdictive'. This framework is based on a series of psychophysical experiments conducted by the authors. Not surprisingly, the postdictive framework elicited criticism from supporters of the models introduced in the previous section.

Here, I will describe the most important aspects of this debate between the competing groups of researchers. To do so, I will first present the series of psychophysical experiments conducted by Eagleman and Sejnowski (2000a) and the results of those experiments. Next, I will describe the postdictive framework the authors derive from their findings. Finally, I will present the main arguments against the postdictive framework made by research groups advocating for a different explanation of the FLE as well as the counterarguments put forward by Eagleman and Sejnowski. When presenting this debate, I will stick to the order of presentation of the various models introduced in the previous

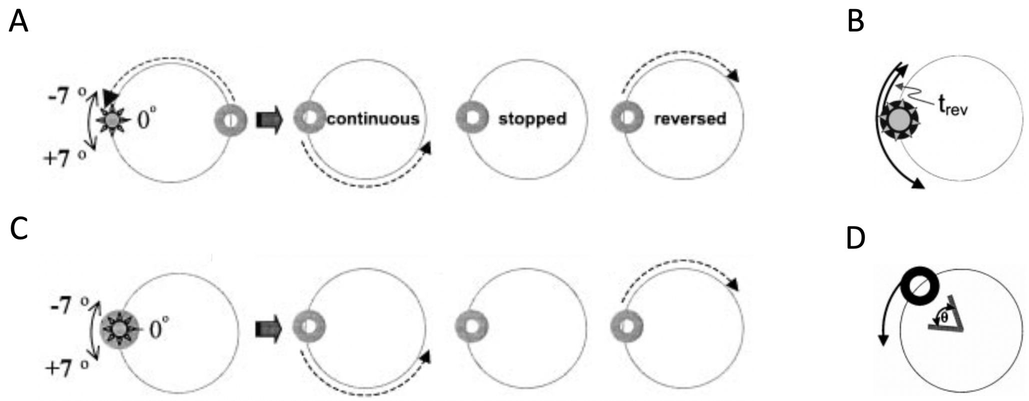

Figure 4. Series of psychophysical experiments conducted by Eagleman and Sejnowski (2000a) to research the FLE. *(A)* A bright white disk is briefly presented co-localised with a moving ring. The latter continues to move along one of three trajectories after the flash. *(B)* Same as in A, with no movement of the ring prior to the flash. *(C)* Similar to B, but the moving ring changes its direction after some period of time. *(D)* Subjects are asked to point to the starting position of a suddenly appearing moving ring using a flashed pointer.

Note. Adapted from "Motion Integration and Postdiction in Visual Awareness," by D. M. Eagleman and T. J. Sejnowski, 2000, *Science, 287*(5460), pp. 2037–2038 (https://doi.org/10.1126/science.287.5460.2036). Copyright 2000 by The American Association for the Advancement of Science.

section (i.e., I will first elaborate on criticism from Whitney and Cavanagh (2000) as well as Patel et al. (2000) before I turn to the arguments made by Krekelberg and Lappe (2000b)).

Experiments & results. The psychophysical experiments conducted by Eagleman and Sejnowski (2000a) are illustrated schematically in Figure 4. As I present the design and the results of these experiments, I will intentionally omit any interpretation of these findings offered by the authors, as I will discuss the postdictive framework separately in the next section.

All of the experiments conducted by Eagleman and Sejnowski (2000a) involve the movement of a ring along a circular trajectory and the presentation of a flashed stimulus. Generally speaking, the variable of interest is always the perceived misalignment between the moving and flashed stimuli.

In the first experiment (Fig. 4 A) conducted by the authors, a ring moves along a circular trajectory at a constant speed of $360°s^{-1}$. As the ring travels along the circular arc that subtends an angle of 14° and is centered around the point opposite to the starting position of the moving ring, a bright white disk is flashed (for approx. $14°/360°s^{-1} \approx 39$ ms). After the flash is presented, the ring either (a) continues its motion, (b) reverses its direction, or (c) stops moving altogether. In a two-alternative forced choice task (2AFC), subjects must report whether they perceived the flashed stimulus above or below the centre of the moving ring. Whereas no perceived displacement is found in condition (b), an identical magnitude of effect is seen in conditions (a) and (c), which differs significantly from the results in condition (b) (Eagleman & Sejnowski, 2000a). In conditions (a) and (c), the flashed white disk is always perceived to lag the moving ring (i.e., it is perceived *above* the moving ring in condition (a) and *below* the moving ring in condition (c)).

The second experiment (Fig. 4 B) is identical to the experiment just described in all but one respect: There is no prior movement of the moving ring. Instead, the flashed disk and the moving ring appear simultaneously on a screen, and the moving ring then takes one of the three trajectories described above. The results of this experiment exactly mirror the results of the first experiment (i.e., no significant difference between the results of the two experiments).

The third experiment (Fig. 4 C) is again quite similar to the second experiment. Once again, the flashed disk and the moving ring simultaneously appear on the screen. This time, however, the ring always starts to move clockwise for some time t_{rev}. Then, the moving ring suddenly changes its direction and moves counterclockwise. The time before reversal is systematically varied from 13–80 ms, and, as before, subjects have to indicate whether they perceived the flashed white disk above or below the moving ring (2AFC). Eagleman and Sejnowski (2000a) report that, as the time before reversal is increased, the perceived misalignment of the flashed stimulus gradually shifts from *above* the moving ring to *below* the moving ring. Additionally, the FLE is effectively abolished with 26 ms before reversal, and it takes about 67–80 ms of clockwise movement of the ring to reproduce the illusory displacement observed in the first two experiments (Eagleman & Sejnowski, 2000a). Note that this is in line with the average time delay of the FLE in the CM paradigm observed by Nijhawan (1994).

In the fourth experiment (Fig. 4 D), subjects are asked to adjust the radial angle θ of a flashed pointer to indicate the starting position of a suddenly appearing ring that moves along a circular trajectory in a clockwise fashion as soon as it is presented. Crucially, the flashed pointer is presented some time Δt *prior* to the moving ring, where

Δt is systematically varied from 0–53 ms. Across all five conditions, subjects consistently "adjusted the pointer to indicate a position an average of $\sim 6°$ ahead of the actual starting position of the ring" (Eagleman & Sejnowski, 2000a, p. 2038). Additionally, the perceived starting position of the ring did *not* vary systematically with the stimulus onset asynchrony (SOA).

Postdiction in visual awareness. Based on the findings of their first two experiments, Eagleman and Sejnowski (2000a) conclude that latency correction by motion extrapolation cannot account for the FLE. If motion extrapolation were in fact the underlying mechanism that drives the illusion, Eagleman and Sejnowski (2000a) argue that the identical 'pre-flash trajectory' in their first experiment should have produced similar results in all three conditions, which it did not. The authors further reinforce this argument by replicating their findings with a nearly identical experimental paradigm that excludes the trajectory of the moving ring prior to the presentation of the flash, thus effectively disposing of any input that could be used by a mechanism solely relying on motion extrapolation.

Eagleman and Sejnowski also claim to have disproven that the differential latency model can account for the FLE. They base this conclusion on the results of their fourth experiment, claiming that if the flash-lag illusion was based on latency differences, giving the flashed pointer a head-start should cancel out the spatial misalignment reported when the pointer and moving ring are presented simultaneously. As this is not the case, the authors conclude that latency differences "are not relevant to the flash-lag effect" (Eagleman & Sejnowski, 2000a, p. 2038).

To explain their experimental findings, Eagleman and Sejnowski offer their own account of the flash-lag illusion, which the authors dub a 'postdictive' framework. The suggested mechanism works as follows: The perceived location of the flashed disk and the moving ring (attributed to the point in time when the flash was presented) is a 'temporally weighted spatial average' of the locations that both stimuli occupy in the roughly 80 ms following the presentation of the flashed disk (Eagleman & Sejnowski, 2000a). Additionally, based on the similarity of the results of the first two experiments (Fig. 4 A & B), the flash supposedly "resets motion integration in the visual system, making motion after the flash effectively like

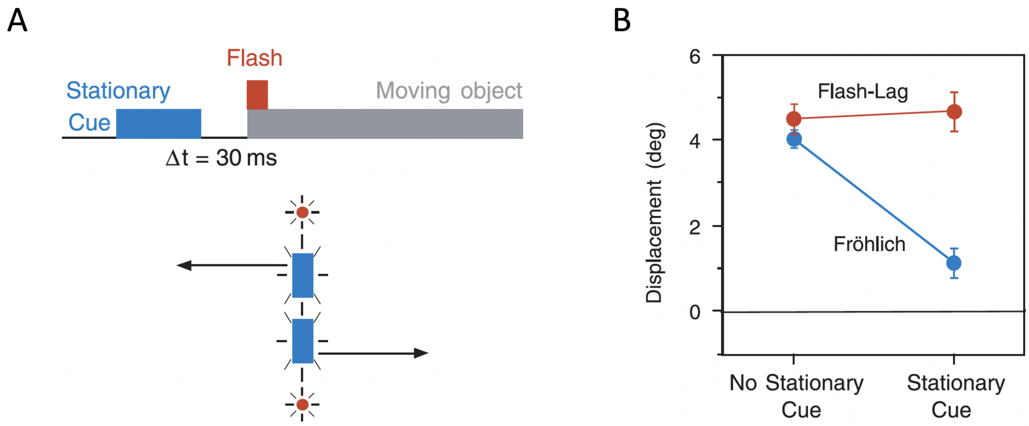

Figure 5. Experiment by Whitney and Cavanagh (2000) to distinguish between Fröhlich effect and flash-lag effect. *(A)* Experimental design. Two rectangular shapes are presented at rest for 2.5 s and subsequently are removed for 30 ms. They then reappear again and instantly begin to move in opposite directions. In an additional experiment, a flash is briefly (15 ms) presented in alignment with the starting position of the rectangular shapes at the onset of motion. *(B)* Results. The presentation of stationary cues only reduces the perceived misalignment in those trials in which no flash is presented at the onset of motion of the rectangular shapes ('Fröhlich' trials, depicted by blue symbols).

Note. Adapted from "The Position of Moving Objects," by D. Whitney and P. Cavanagh, 2000, *Science, 289*(5482), p. 1107a (https://doi.org/10.1126/science.289.5482.1107a). Copyright 2000 by The American Association for the Advancement of Science.

motion that starts de novo" (Eagleman & Sejnowski, 2000a, p. 2037). Hence, the model proposed by Eagleman and Sejnowski is similar to the temporal integration hypothesis advocated for by Lappe and Krekelberg (1998), with the subtle differences that (a) the integration window is reset every time a flashed stimulus is presented, and (b) the perceived misalignment in the FLE is explicitly 'postdicted' to the time of the flash.

Criticism. Soon after Eagleman and Sejnowski had proposed the postdictive framework, advocates of other accounts of the FLE criticised different aspects of the model.

Whitney and Cavanagh (2000), for example, criticise the fourth experiment (adjustment of flashed pointer) carried out by Eagleman and Sejnowski (2000a) and the conclusions drawn from the results of this experiment. In particular, Whitney and Cavanagh claim that the fourth experiment conducted by Eagleman and Sejnowski captures the Fröhlich effect instead of the FLE and argue that these two illusions do not share the same underlying mechanisms. Accordingly, Whitney and Cavanagh remark that Eagleman and Sejnowski's fourth experiment is not a test of the differential latency model, which hence "remains a viable explanation of flash-lag data" (Whitney & Cavanagh, 2000, p. 1107a).

To back their claim that Fröhlich effect and FLE are not the same, Whitney and Cavanagh (2000) present experimental evidence suggesting that the Fröhlich effect can be reduced significantly by cueing the starting position of suddenly appearing stimuli, whereas stationary cueing does not seem to reduce the FLE (see Fig. 5 for more).

While the most powerful argument made by Whitney and Cavanagh is certainly the differentiation between Fröhlich effect and FLE, the authors also point out that their findings (reduced Fröhlich effect due to stationary cueing) contradict the reset mechanism of motion integration proposed by Eagleman and Sejnowski (2000a): "According to postdiction, the invisibility of motion initiation should not depend on events before the onset of motion, because the motion onset itself resets all ongoing integrals" (Whitney & Cavanagh, 2000, p. 1107a).

It is also important to note that Whitney and Cavanagh acknowledge that *their* differential latency model cannot account for the Fröhlich effect (Whitney & Cavanagh, 2000). In contrast, the FIC paradigm of the differential latency model proposed by Öğmen et al. (2004) does indeed account for the Fröhlich effect, as explained earlier.

This same group of researchers, Patel et al. (2000), also attack Eagleman and Sejnowski on the basis of their fourth experiment and argue that the results obtained by Eagleman and Sejnowski (2000a) are indeed consistent with the FIC paradigm of the differential latency hypothesis. Patel et al. point out that the results of Eagleman and Sejnowski's fourth experiment should depend on the dynamics of the computational process (transient phase vs. steady state, Fig. 2 B) determining the moving object's position as well as the SOA *if* subjects are instructed to judge "the spatial misalignment between the flashed and moving objects at the instant the flashed object is perceived" (Patel et al., 2000, p. 1051a). *If*, however, participants use the flashed pointer "to point to the beginning of the trajectory of the moving ring" (Eagleman & Sejnowski, 2000a, p. 2037), than the FIC paradigm predicts that the observer's reports will be independent of the SOA, which is precisely what Eagleman and Sejnowski (2000a) have found.

Additionally, Patel et al. (2000) remark that the postdictive framework by Eagleman and Sejnowski could not possibly make different predictions for the CM and FIC paradigms since the resetting of motion integration due to flashed stimuli essentially renders the one key difference between these two paradigms (i.e., motion before the flash) irrelevant. In contrast, the differential latency hypothesis does make different predictions for the two paradigms given that the flashed stimulus' latency L_f is *shorter* than the time it takes the computational process to reach its steady state (Fig. 2 B).

In particular, Patel et al. (2000) point to experiments conducted earlier that have reported a flash-*lead* effect (Purushothaman et al., 1998), something that, in their opinion, cannot be predicted by the postdictive framework due to its motion integration reset mechanism.

Once more, this resetting mechanism also receives criticism from Krekelberg and Lappe (2000b), the duo of researchers that developed the temporal integration model. As mentioned before, the temporal integration model predicts the FLE to be less pronounced if the outer dots of the experimental setup depicted in Figure 3 A are flashed more often, which has been confirmed experimentally (Krekelberg & Lappe, 1999; Lappe & Krekelberg, 1998). This finding of Krekelberg and Lappe contradicts the resetting of motion integration by flashed stimuli: If each flash does indeed reset the motion integration process, then the observed FLE should not decrease with an increased number of flashes.

Finally, Krekelberg and Lappe criticise that "there is no need to 'postdict' the perceived offset to the time of the flash" (Krekelberg & Lappe, 2000b, p. 1107a). In their opinion, the fact that motion of the moving object *after* the flash is taken into account is simply a consequence of the delays inherent to information processing by the visual system rather than an expression of a postdictive nature of visual perception.

Counterarguments. At the core of Eagleman and Sejnowski's response (Eagleman & Sejnowski, 2000b, 2000c) to the criticism voiced by Whitney and Cavanagh, Patel et al., as well as Krekelberg and Lappe, lies an expansion of the postdictive framework. Primarily, Eagleman and Sejnowski revise the motion integration reset mechanism to address the criticism voiced by the research groups mentioned above. Instead of the resetting mechanism being an 'all-or-none switch', Eagleman and Sejnowski (2000b, 2000c) suggest that the visual system continuously compares its 'internal model of external stimuli' with newly acquired 'external measurements' and that the visual system 'devalues' its internal model "as the consequence of an unpredicted event (such as a flash)" (Eagleman & Sejnowski, 2000c, p. 1051a). In particular, this devaluation ought to depend on the salience of the surprising stimulus (Eagleman & Sejnowski, 2000b, 2000c).

This revised model of the resetting mechanism is the basic building block of Eagleman and Sejnowski's responses to the three research groups that had criticised the postdictive framework (i.e., Krekelberg & Lappe, 2000b; Patel et al., 2000; Whitney & Cavanagh, 2000). I will now present these individual responses one by one, sticking to the order of presentation that I have employed twice before.

Regarding the experiment conducted by Whitney and Cavanagh (2000) to plot Fröhlich effect and FLE against each other, Eagleman and Sejnowski remark that "more than one parameter was changed between conditions" (Eagleman & Sejnowski, 2000b, p. 1107a), indirectly suggesting that the results of the experiment do not necessarily reflect separate underlying mechanisms of these two effects. Further, Eagleman and Sejnowski claim that their revised model of the postdictive framework can indeed explain the findings of Whitney and Cavanagh: Since the sudden onset of the moving blocks is less surprising in the cued condition with no flash being presented (and hence 'only moderately salient'), the internal model ought to be devalued to a lesser extent, resulting in a smaller perceived displacement compared to the other three conditions. In these three conditions, the salience of the stimulus ought to be larger (due to the uncued, sudden onset of motion or the flash, or both), leading to a more considerable devaluation of the internal model and a more significant illusory displacement (Eagleman & Sejnowski, 2000b).

Eagleman and Sejnowski follow a very similar line of argument in addressing the criticism voiced by Patel et al. (2000): The authors claim that flash-*lead* effects are indeed possible within the postdictive framework by simply "modifying the saliences of the flash and the moving target" (Eagleman & Sejnowski, 2000c, p. 1051a). If this were done, the internal model would then be 'more resistant to devaluation'. Consequently, more of the pre-flash trajectory of the moving object would be taken into account, thus making flash-lead effects possible in the CM paradigm under the postdictive framework (Eagleman & Sejnowski, 2000c).

Additionally, Eagleman and Sejnowski present results of an experiment that they claim disproves "the fundamental assumption of the differential-latency model" (Eagleman & Sejnowski, 2000c, p. 1051a). According to the authors, this fundamental assumption is that flashed stimuli take longer to reach awareness than moving objects. If this were the case, the temporal order of a flashed and moving object presented in quick succession should be misperceived, depending on the order of presentation and the SOA, so Eagleman and Sejnowski (2000c). Since this is not what Eagleman and Sejnowski find, the authors conclude that the differential latency hypothesis must be fundamentally flawed.

Finally, Eagleman and Sejnowski also address the multiple-flash experiment presented by Krekelberg and Lappe (2000b) and the author's criticism that the postdictive framework cannot account for the results of this experiment. To combat this claim, Eagleman and Sejnowski (2000b) once more retreat to their revised model of the resetting mechanism: Because a series of flashes presented periodically ought to be less surprising, the internal model is devalued to a lesser extent (compared to a single flash), and hence a smaller illusory displacement is reported.

On top of this, Eagleman and Sejnowski also replicate the experiment conducted by Krekelberg and Lappe (2000b), adding a further condition: "On half the trials the outer dots [are] flashed at unpredictable times but at the same average rate" (Eagleman & Sejnowski, 2000b, p. 1107a). Eagleman and Sejnowski argue that the decrease in the predictability of the flashes should lead to an increase in the reported illusory displacement (based on their revised model), and this is precisely what they find; the reported illusory displacement being almost double that of the 'predictable' condition (Eagleman & Sejnowski, 2000b). Finally, Eagleman and Sejnowski contend that the temporal integration hypothesis by Krekelberg and Lappe cannot explain these findings.

Discussion

Following the rediscovery of the flash-lag illusion by Nijhawan (1994), many research groups have proposed different accounts of the mechanisms underlying this illusion, such as motion extrapolation, temporal integration and differential latency, to name a few. Based on a series of psychophysical experiments, Eagleman and Sejnowski (2000a) claim that neither motion extrapolation nor the differential latency hypothesis can account for the FLE. In this final part, I will take a closer look at the experimental evidence provided by Eagleman and Sejnowski and the authors' conclusions.

Based on their first two experiments (Fig. 4 A & B), Eagleman and Sejnowski (2000a) conclude that it is 'untenable' to explain the FLE based on motion extrapolation as initially proposed by Nijhawan (1994). None of the researchers involved in the debate presented here challenge this claim. Neither would I for the simple reason that the experimental evidence is too compelling: It is hardly comprehensible that an identical pre-flash trajectory could lead to qualitatively different perceptual illusions (moving ring *above* vs. *below* flashed disk) for different post-flash trajectories, assuming that motion extrapolation is the sole mechanism at work in the FLE. Motion extrapolation certainly cannot explain the observed flash-lag illusion in the FIC paradigm utilised in the second experiment conducted by Eagleman and Sejnowski (2000a) as there is simply no prior motion trajectory to extrapolate from. Whereas at first glance, it sounds more plausible that motion extrapolation could be influencing the illusion in the CM paradigm, the striking similarity of results between the first and second experiment also renders this possibility highly unlikely, in my opinion.

In addition, Eagleman and Sejnowski reason that it is the motion of the moving object *after* the flash that causes the illusion and that the visual system integrates this information via a 'temporally weighted spatial averaging' process (Eagleman & Sejnowski, 2000a). Once again, this claim does not cause any debate as both the temporal integration hypothesis and the differential latency theory base their predictions on computations that involve motion *after* the flash.

What does spark an intense debate, however, is the reset mechanism proposed by Eagleman and Sejnowski. Since the results of the second experiment are virtually identical to those of the first experiment, Eagleman and Sejnowski hypothesise that the flash *resets* the motion integration process, hence causing the pre-flash trajectory to lose any significance it may have otherwise had in the computational process that determines the moving object's position (Eagleman & Sejnowski, 2000a). This hypothesis is heavily criticised by Krekelberg and Lappe (2000b), Patel et al. (2000), and Whitney and Cavanagh (2000), and all three research groups point to experimental evidence that is seemingly incompatible with the proposed reset mechanism. To resolve these incompatibilities, Eagleman and Sejnowski (2000b, 2000c) offer a revised version of their framework, which essentially differs from the initial model only in the workings of the reset mechanism: Instead of performing a hard reset, the visual system ought to discard just some of the information collected before the flash and the proportion of information that is discarded ought to depend, inter alia, on the saliency of the flash. While this may sound sensible, and it certainly helps to reduce the inconsistencies pointed out by competing researchers, it causes the postdictive model to become less attractive, in my opinion. Essentially, what remains is a model that is built on 'spatiotemporal integration' with both the size of the integration window and its position in time being flexible (Eagleman & Sejnowski, 2000c). Phrased provocatively, the expanded postdictive framework offered by Eagleman and Sejnowski is nothing more than a modification of the temporal integration hypothesis proposed by Lappe and Krekelberg, made more flexible by leaving the technical details of the precise computational process largely unspecified.

By referring to their third experiment (Fig. 4 C), Eagleman and Sejnowski (2000a) conclude that the time window of information after the flash that is taken into account is likely to span approximately 80 ms. This finding is not discussed further by any of the research groups, perhaps because it merely adds some quantitative detail but does *not* seem to qualitatively facilitate the uncovering of the mechanisms at work in the flash-lag illusion.

Last but not least, Eagleman and Sejnowski (2000a) also claim, based on the results of their fourth experiment (Fig. 4 D), to have disproven the possibility that differential latency may be what is driving the flash-lag illusion. Not surprisingly, this statement does receive harsh criticism from Patel et al. (2000) and Whitney and Cavanagh (2000). Both groups of authors point out that Eagleman and Sejnowski are observing and researching the Fröhlich effect in their fourth experiment, not the flash-lag illusion, and I certainly side with Patel et al. and Whitney and Cavanagh on this. Whereas the latter present experimental evidence suggesting that Fröhlich effect and FLE can be disentangled (Whitney & Cavanagh, 2000), Patel et al. (2000) provide a compelling explanation of how their differential latency model predicts exactly the results found by Eagleman and Sejnowski (2000a) under the FIC paradigm.

Overall, Eagleman and Sejnowski (2000a) do provide compelling evidence against the motion extrapolation theory postulated by Nijhawan (1994). However, I disagree that their experimental findings rule out the possibility of differential latency being one of the mechanisms driving the flash-lag illusion. On top of that, their proposed framework lacks technical details, which makes it difficult to test the framework and plot it against competing theories fairly. As it stands, the postdictive framework appears to be an incomplete, modified version of the temporal integration hypothesis, with many questions left unanswered.

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