TECHNICAL COMMENT

Flash-Lag Effect: Differential Latency, Not Postdiction

A continuously moving object typically is perceived to lead a flashed object in space when the two retinal images are physically aligned, a phenomenon known as the flash-lag effect (*1*). Eagleman and Sejnowski (*2*) recently published data that they interpreted to disagree with a previous explanation of this phenomenon, the differential-latency hypothesis (*3–7*), and to support instead a postdiction hypothesis (*8*). Here we demonstrate that the data presented in (*2*) are fully consistent with the differential-latency hypothesis. We also provide evidence that rejects postdiction as an explanation for the flash-lag phenomenon.

According to Eagleman and Sejnowski (*2*), the differential-latency hypothesis predicts that the perceived flash-lag should change if the flash is temporally advanced. To test that prediction, they used a flash-initiated cycle (FIC) paradigm in which the onset of the moving object occurs synchronously with the flash (Fig. 1A). Observers were asked to "adjust the angle of a 'pointer' line . . . to point *to the beginning of the trajectory* of the moving ring" (emphasis added). Eagleman and Sejnowski found that the adjusted angle of the pointer did not depend on the stimulus onset asynchrony (SOA) between the flashed and moving objects. That finding, however, does not contradict the differential-latency hypothesis, which predicts that the flash misalignment will depend not only on the SOA but also on the dynamics of the process that computes the moving object's position (compare s and s′ in Fig. 1A), as long as the observer judges the spatial misalignment between the flashed and moving objects at the instant the flashed object is perceived. That instant in time provides a necessary temporal reference for comparing the position of the moving and flashed objects. If, by contrast, observers use the flashed object as a "spatial pointer" to the perceived starting locus of the moving object's trajectory—at s* rather than s in Fig. 1A, because of the Fröhlich effect [(*9*), cited in (*10*)]—the differential-latency hypothesis predicts that observers' reports of s* will not depend on the SOA (*11*).

The postdiction hypothesis states that the position of the moving object is computed de novo after the occurrence of the flash. Consequently, the flashed object is predicted never to spatially lead the moving object. We have shown (*5*), however, that the perceived misalignment between an object in continuous motion (CM) and a flashed object changes from a flash-lag to a flash-lead if the luminance of the flashed object is increased enough (Fig. 1B). Further, whereas the postdiction hypothesis predicts that the perceived misalignment in the FIC and CM conditions should always be equal, our experiments indicate that perceived misalignments differ significantly depending on which condition is used (Fig. 1C). Differential latency can account for that result if, in the FIC paradigm, the flashed object is perceived during the transient phase of the moving object's position computation process (compare s′ in Fig. 1, A and B). In the FIC paradigm, perception of the flashed object is expected to occur during this transient phase of processing because the latency of a high-luminance flash should be relatively short (L'_f in Fig. 1) and the latency of a low-luminance moving line should be relatively long. The differential-latency hypothesis predicts that the perceived misalignment will be equal in the FIC and CM paradigms, as found in (*2*), if the perception of the flashed object occurs when the position computation for the moving object is in steady state (*12*).

Based on their interpretation of the differential-latency hypothesis, Eagleman and Sejnowski inferred from their experimental results that "the visual system only uses information from the 10 to 20 ms after the flash" (*13*). However, when they (*2*) modified the FIC paradigm so that the moving object reversed its direction after an adjustable delay, they observed a change in reversal times beyond 10 to 20 ms. Their conclusion that those data are inconsistent with the differential-latency hypothesis, however, failed to consider the dynamics of the position computation process for the moving object (*6, 7*). In their paradigm, the later the moving object reverses its direction, the less time the position computation process has to reach steady state after the reversal of motion occurs. Therefore, as the reversal time is increased,

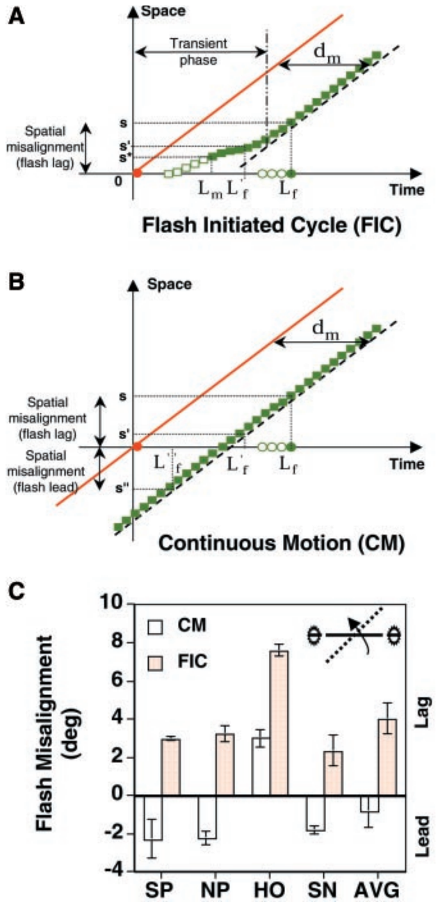

Fig. 1. (**A**) Space-time diagram illustrating the stimuli and the predictions of our differential-latency hypothesis in the FIC paradigm. Stimuli are shown in red; responses of the perceptual system are depicted in green. Initially, the flashed object is presented briefly at the starting spatial location of the moving object (red circle at the origin). The position of the moving object then changes at a constant speed (red line). The green squares and circles depict the computed perceptual positions of the flashed and the moving objects, respectively. The flashed and the moving objects become visible at different latencies, indicated by L_f and L_m, respectively, at spatial locations 0 and s*. The filled squares and circles indicate the part of the trajectory where these objects are visible. At the time the flashed object becomes visible (L_f), the perceived position of the moving object is s. Therefore, even though the flashed and the moving objects are physically presented at the same spatial location (the origin), the flashed object is perceived to spatially lag the moving object by s. If the latency of the flashed object decreases from L_f to L'_f because of a change in the stimulus parameters, then the spatial misalignment between the moving and flashed objects changes from s to s′. When the position computation process for the moving object reaches steady state (indicated by the filled green squares running parallel to the dashed lines), the differential latency is given by ($L_f - d_m$). (**B**) CM paradigm, in which the motion of the moving object starts long before the presentation of the flashed object, so that the position computation process for the moving object is in steady state. If the latency of the flashed object is very short (L''_f), then it is perceived to spatially lead the moving object by s″. (**C**) The perceived spatial flash misalignment (±1 SEM) between a high-luminance flashed object (76.3 cd/m^2) and a low-luminance moving object (4.8 cd/m^2), measured as the degrees of orientation of the rotating line, in the FIC and CM paradigms for four observers (two naïve), and the average across the observers (AVG). The background luminance was 0.05 cd/m^2. The speed of rotation was 8.3 rpm. The mean difference between the FIC and CM results was 4.85° ± 1.18° [$F(1,3) = 44.63$, $p = 0.007$]. Three of the four observers showed a flash-lead in the CM condition, in accordance with (*5*).

the flash misalignment is increasingly determined by the transient dynamics of the position computation process. The differential-latency hypothesis cannot predict the relationship between perceived flash misalignment and the motion-reversal time without additional information about the transient dynamics of the position computation process (*14*).

In summary, the data of Eagleman and Sejnowski are fully consistent with the differential-latency hypothesis. Further, the postdiction hypothesis is unable to account for the occurrence of a flash-lead when the luminance of the flashed object is sufficiently high, or for data reported here that show the effect of the initial motion trajectory on perceived misalignment.

Saumil S. Patel*
Haluk Ogmen
Department of Electrical
& Computer Engineering
College of Engineering
University of Houston
Houston, TX 77204, USA
E-mail: ogmen@uh.edu

Harold E. Bedell
Vanitha Sampath
College of Optometry
University of Houston

Also College of Optometry, University of Houston.

References and Notes

1. D. MacKay, *Nature* **181**, 507 (1958).
2. D. M. Eagleman, T. J. Sejnowski, *Science* **287**, 2036 (2000).
3. Relative mislocalization between a flashed and moving object based on differential latency was proposed by Metzer (*15*), as cited by Mateeff and Hohnsbein (*16*).
4. M. V. C. Baldo, S. A. Klein, *Nature* **378**, 565 (1995).
5. G. Purushothaman, S. S. Patel, H. E. Bedell, H. Ogmen, *Nature* **396**, 424 (1998).
6. D. Whitney, I. Murakami, *Nature Neurosci.* **1**, 656 (1998).
7. ———, P. Cavanagh, *Vision Res.* **40**, 137 (2000).
8. Eagleman and Sejnowski proposed a modified version of a hypothesis originally formulated by MacKay (*1*) that stipulates that the perceptual system updates the position of objects only after a significant amount of evidence is amassed for positional change.
9. F. W. Fröhlich, *Z. Sinnesphysiol.* **54**, 58 (1923).
10. M. Alpern, *J. Opt. Soc. Am.* **43**, 648 (1953).
11. The outcome of the experiment depends on the observer's ability to judge spatial misalignment in the presence of temporal asynchrony (*17*).
12. We tested this prediction by using a high luminance for the moving object (relatively shorter latency) and a low luminance for the flashed object (relatively longer latency). Relative to the data in Fig. 1C, we found a significant reduction in the difference between the perceived flash misalignment in the FIC and CM paradigms [mean difference = 1.21° ± 0.93°, $F(1,3) = 44.96$, $p = 0.007$]. For two of the observers, this difference was virtually zero.
13. Regardless of whether 10 to 20 ms refers to the time interval after the presentation or the perception of the flash, the amount of information used by the position computation process depends on its dynamic properties (that is, on the memory of this process), and the differential latency alone is not sufficient to predict it.
14. As an example, assume that the position computation process is a first-order linear unit-gain low-pass system (*6*, *7*) with a time-constant of 23 ms. Using a differential latency of 16 ms and keeping the spatial misalignment in the CM and the FIC paradigm similar to each other (within about 25%), as observed by Eagleman and Sejnowski, the spatial misalignment as a function of reversal time continues to change up to a value of about 40 ms, which is substantially beyond 16 ms.
15. W. Metzer, *Psychol. Forsch.* **16**, 176 (1932).
16. S. Mateeff, J. Hohnsbein, *Vision Res.* **28**, 711 (1988).
17. L. Matin, J. Pola, E. Matin, E. Picoult, *Vision Res.* **21**, 647 (1981).
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Response: Patel *et al.* report conditions in which the flash-lag effect becomes a flash-lead effect (*1*) and question whether this is consistent with our postdictive model (*2*). We show here that their data are indeed consistent with postdiction and provide evidence that rejects differential latency as an explanation.

The fundamental assumption of the differential-latency model is that a flash takes longer to reach awareness than a continuously moving object. A necessary consequence is that flashed and moving objects that are simultaneous in the world will be perceived with an illusory temporal order (Fig 1A). To assess the differential-latency model, we asked participants to fixate a bar in rotary motion on a computer monitor. After 500 ms of rotation, end segments were flashed for 14 ms (at a random orientation within ±20° of the bar). At some time before or after the video frame with the flash, the spinning bar halted movement, and it remained stopped for the rest of the trial.

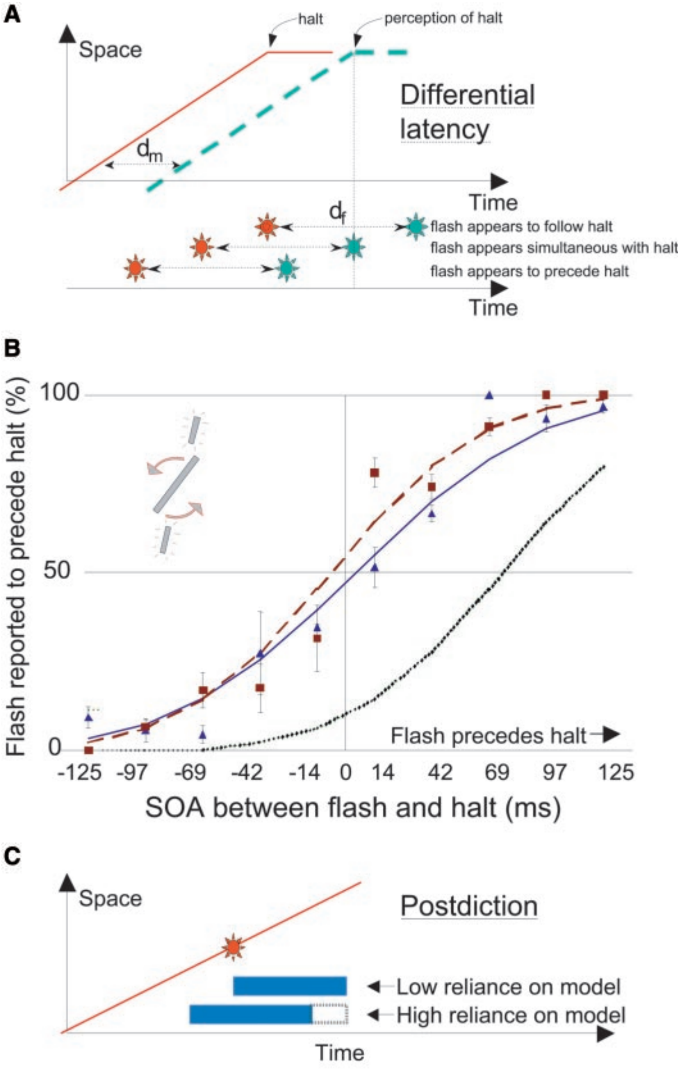

Fig. 1. Comparing differential latency with postdiction. (**A**) Space-time diagram, after Patel *et al.*, illustrating the differential-latency framework. Red represents events in the world; green represents perception of those events. As prescribed by the differential-latency model, flashed objects are assumed to have a delay before reaching awareness (d_f) that is longer than the delay for moving objects (d_m). As a result, differential latency predicts that a flash that occurs at the same time as a change in movement (in this case, a halt) will be perceived to follow the change. For perceived simultaneity, the flash would have to appear well before the halt. (**B**) Participants compare the temporal order of a flash and the halting of a rotating bar (inset shows schematic drawing of stimulus used). Bar subtends 5° visual angle and rotates at 60 rpm; the luminance of the flash cd/m^2. SOA between the flash and halt are varied over 250 ms. Results show that participants do not display an illusory misalignment of temporal order. Symbols show averages from three participants in two conditions: high-luminance bar (42.3 cd/m^2; triangles fit with solid line) or low-luminance bar (1.9 cd/m^2, squares fit with dashed line). The dotted line shows the psychometric curve predicted by the differential-latency model for a differential latency of 80 ms. (**C**) In the postdiction framework, the temporal window of integration can have different positions, sizes, or both, depending on the parameters of the stimuli. Rectangles represent the window of time from which positional information is weighted most heavily. A perceptual decision regarding the position of the moving object when the flash occurred is determined only after positional data from the window of integration has been collected.

Instead of reporting on the alignment of the flashes, as in traditional flash-lag experiments, participants were asked to report which event occurred first—the flash or the halting of the bar. Participants reported the temporal order without misperception (Fig. 1B), which indicates that it does not take longer to perceive a flash than a moving object. The differential-latency framework, by contrast, predicts a systematic shift in the data (dotted curve in Fig. 1B). The same result was obtained with both high- and low-luminance moving bars (Fig. 1B), as well as with a direction reversal or disappearance of the moving bar instead of a halt (data not shown). These results are consistent with evidence that the brain keeps excellent track of the temporal order of events (*3*, *4*).

The results of Patel *et al*. are consistent with an expanded postdiction framework we have recently presented (*5*) for understanding the flash-lag effect under more general conditions. Our framework is summarized by three assumptions: (i) The visual system compares dynamic internal models to stimuli in the external world. These internal models are developed, in part, from information integrated in a recent window of time (*6*, *7*). (ii) As the consequence of an unpredicted event (such as a flash), the visual system devalues its internal model and relies more heavily on newly collected measurements—a strategy that reflects its imperfect prediction of the outside world (*5*). In the conditions used in our original report (and reflected in note 12 of Patel *et al*.), internal models can be devalued completely (i.e., reset) by the flash, and the fresh collection of information leaves the system in the same condition as de novo movement. In that case, the FIC and CM conditions will be expected to yield the same perceived displacement (*2*). (iii) The devaluation of previously collected information does not have to be all-or-none. In different experimental conditions, information before the flash will be retained to greater or lesser degrees. This will depend not only on the salience of the flash, as demonstrated in (*5*), but also on the salience of the moving object. Specifically, the degree to which the internal model is relied upon depends in part on the confidence of the external measurements (detectability) of the moving object.

In our framework, the low-luminance moving object used by Patel *et al*. engenders a low signal-to-noise ratio in the measurements. In that situation, the visual system depends more heavily on its internal model than on external measurements (*7*). When reliance on the internal model is stronger, a smaller amount of information that was collected before the flash is discarded. Within this framework, it is clear how a flash-lead is possible: The internal model is more resistant to devaluation, such that more pre-flash information is carried over into the interpolated (postdictive) position estimation. In this case, the CM condition can yield a flash-lead.

The postdictive framework is illustrated in Fig 1C. Positional information about the moving object is integrated from a window of time around the flash, and this positional information is interpolated to yield a position estimate. By modifying the saliences of the flash and the moving target, one can change the size or position of the window of spatiotemporal integration, such that the interpolated answer will yield flash-lag or flash-lead illusions. Such an interpolation implies that the perceptual decision is not reached until further positional data, including information after the flash, has entered the visual system. Thus the final answer is postdictive: The visual system can employ positional data that happened after the flash when making its perceptual decision about what happened at the moment of the flash.

The data presented by Patel *et al*. are consistent with postdiction. In contrast, a differential-latency framework is inconsistent with a test of its key assumptions (Fig. 1B). Our results suggest that the flash-lag effect is a spatial illusion, not a temporal one (*8*).

David M. Eagleman
Sloan Center for Theoretical Neurobiology
Salk Institute for Biological Studies
10010 North Torrey Pines Road
La Jolla, CA 92037, USA
Terrence J. Sejnowski
Howard Hughes Medical Institute
Salk Institute for Biological Studies
and Department of Biology
University of California at San Diego
La Jolla, CA 92093, USA

References and Notes

1. G. Purushothaman, S. S. Patel, H. E. Bedell, H. Ogmen, *Nature* **396**, 424 (1998).
2. D. M. Eagleman, T. J. Sejnowski, *Science* **287**, 2036 (2000).
3. R. Efron, *Percept. Psychophys.* **14**, 518 (1973).
4. These results are also consistent with those reported in figure 3 of (*2*), in which participants were asked to point at the perceived starting point of the moving object. If there were a differential latency between flashed and moving objects, then one would expect the flashed pointer to become visible after the appearance of the moving object, even when it was actually presented on-screen just before. On the contrary, the flash always veridically appeared before appearance of the moving ring when it was presented that way. That is why participants were asked to remember where the flashed line was pointing, and to align it with their first perception of the ring.
5. D. M. Eagleman, T. J. Sejnowski, *Science* **289**, 1107a (2000), www.sciencemag.org/cgi/content/full/289/5482/1107a.
6. D. C. Knill, W. Richards, Eds., *Perception as Bayesian Inference* (Cambridge Univ. Press, Cambridge, UK, 1996).
7. R. P. Rao, *Vision Res.* **39**, 1963 (1999).
8. That the temporal relationship of moving and flashed objects is not illusory can readily be seen in a demonstration at www.cnl.salk.edu/∼eagleman/flashlag.

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Saumil S. Patel, Haluk Ogmen , Harold E. Bedell and Vanitha Sampath

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