When visual attention is divided in the flash-lag effect

Jane Yook[1,2,3], Hinze Hogendoorn[1,4], Gereon R. Fink[2,5], Simone Vossel[2,3]*, Ralph Weidner[2]*

*These authors contributed equally

[1] Melbourne School of Psychological Sciences, The University of Melbourne, Melbourne VIC 3010, Australia

[2] Cognitive Neuroscience, Institute of Neuroscience and Medicine (INM-3), Forschungszentrum Jülich, 52428 Jülich, Germany

[3] Department of Psychology, Faculty of Human Sciences, University of Cologne, 50923 Cologne, Germany

[4] School of Psychology and Counselling, Queensland University of Technology, Brisbane QLD 4059, Australia

[5] Department of Neurology, Faculty of Medicine, University Hospital Cologne, University of Cologne, 50923 Cologne, Germany

Abstract

The flash-lag effect (FLE) is the perceived lagging behind of a flash physically aligned to a continuously moving object. The illusion is attributed to a compensatory mechanism of motion extrapolation, which ensures that the perceived position of a moving object aligns with its real-time position despite neural processing delays. While several studies have demonstrated that attention can modulate the FLE, the precise role of attention in the extrapolation process remains elusive. Thus, in the current study, we sought to disentangle the influence of visual attention by manipulating the amount of attention allocated to moving stimuli in different locations. By directing attention to one, two, three, or four stimuli presented in different quadrants across trials, we measured the trial-wise FLE to investigate potential FLE magnitude or variability modulations under different attention conditions. Our results showed that FLE magnitudes were significantly larger when attention was divided among two, three, or four stimuli than when attention was focused on one stimulus. Surprisingly, FLE variability showed no difference across attention conditions. These findings show that the compensatory mechanisms for neural processing delays in dynamic environments are modulated by attention to enable efficient processing of multiple objects simultaneously.

Keywords

Flash-lag effect, attention, divided attention, motion extrapolation, neural processing delays, multiple objects

1. Introduction

The flash-lag effect (FLE) is a classic demonstration of a motion-induced position shift. As initially shown by Mackay (1958), the illusion occurs when a static object flashes next to a continuously moving object, leading to a perceived spatial offset between their positions despite their physical alignment at the moment of the flash. Specifically, the flash is misperceived as lagging behind the moving object.

While the FLE has garnered many explanations including theories of attention shifts, differential processing latency, temporal position averaging, postdiction, and discrete perception (Baldo & Klein, 2010; Brenner & Smeets, 2000; Eagleman & Sejnowski, 2000; Khurana et al., 2000; Krekelberg & Lappe, 1999, 2001; Purushothaman et al., 1998; Schneider, 2018; Whitney & Murakami, 1998), motion extrapolation provides a parsimonious explanation. This mechanism compensates for inherent delays in perceptual processing (Nijhawan, 1994, 2002, 2008), already operating on early stages of visual processing (Johnson et al., 2023). It ensures that the perceived position of a moving object aligns more closely with its veridical position. In the context of the FLE, the predictable motion trajectory of the moving object allows for extrapolation. In contrast, the static flash, having no motion trajectory, cannot compensate for neural delays through extrapolation, resulting in the misperception of the flash as lagging (Murakami, 2001).

Our limited processing capacity poses a challenge for motion extrapolation in dynamic environments with multiple moving objects (cf. multiple object tracking; Pylyshyn & Storm, 1988; see also Adamian & Andersen, 2022; Howe & Holcombe, 2012; Luu & Howe, 2015). Our attentional capacity may be insufficient to track the motion of all objects simultaneously (Norman & Bobrow, 1975), necessitating a strategic allocation of cognitive resources to focus on information most relevant to behavior. For example, spatial attention enhances processing at specific locations in anticipation of a task-relevant stimulus (Posner, 1980; for review, see Reynolds & Chelazzi, 2004; Summerfield & Egner, 2009). This prompts the intriguing question: how does the allocation of attention influence the ability to predict motion, particularly in the FLE?

Several studies have demonstrated that variations in attentional resources can modulate the FLE. For instance, Sarich et al. (2007) employed a dual-task paradigm to compare the magnitude of the FLE in a flash-lag task performed alone or concurrently with a target detection task. They found that the FLE, measured as a point of subjective equality, was smallest when the flash-lag task was performed separately or with a slight interval from the detection task. Notably, when another task necessitated attention, the magnitude of the FLE increased (and detection worsened). Similarly, Shioiri et al. (2010) manipulated attention by varying the number of stimuli moving and presenting the flash next to one of these stimuli. They observed an FLE increase when attention was divided among two or six stimuli but an FLE decrease when focused solely on one stimulus. Furthermore, when participants were pre-cued to upcoming flash locations, the FLE reduced following valid cues compared to invalid cues (Baldo & Klein, 2010; Namba & Baldo, 2004; Vreven & Verghese, 2005; but see Khurana et al., 2000) or no cues (Shioiri et al., 2010). However, the specific implications of these findings for the role of attention in motion extrapolation supposed to underlie the FLE remain unclear.

While attentional mechanisms prioritize and allocate resources to relevant features or stimuli, they could play a role in facilitating or modulating the extrapolation process. Extrapolation may become prioritized in the context of divided attention, where attentional resources are distributed across multiple objects. When detailed processing resources are limited, the brain may rely more heavily on predictive mechanisms to maintain coherence in perception. In this sense, the brain might compensate for the reduced attentional focus by generating predictions of each object's future position based on generalized motion information. This could lead to a trade-off in the accuracy and precision of predictions, potentially increasing the magnitude and variability of the FLE. Furthermore, divided attention could lead to delays in processing motion information. Studies have demonstrated that when attention is divided among multiple tasks or stimuli, processing efficiency is compromised, leading to slower reaction times and delays in accessing relevant information (Carrasco & McElree, 2001; Giordano et al., 2009). This time-consuming process could be prolonged (cf. temporal integration; Lappe & Krekelberg, 1998), resulting in slower recognition of motion and delayed availability of position information for each object. The brain may attempt to extrapolate over larger distances to compensate for these delays, potentially increasing the FLE

magnitude. These possibilities suggest that the brain may prioritize efficiency over reliability of motion processing.

Alternatively, divided attention may disrupt or attenuate the extrapolation process altogether. When attention is divided, cognitive resources may be insufficient to accurately anticipate multiple objects' trajectories simultaneously. This disruption could be limited by the quality of motion information, such as spatial resolution (Anton-Erxleben & Carrasco, 2013; Barbot & Carrasco, 2017; Yeshurun & Carrasco, 1998, 1999). The brain may fail to generate reliable predictions about each object's future positions, leading to errors or inconsistencies in perception. The perceived position of the flash relative to the moving object may vary widely from trial to trial, potentially increasing FLE variability.

The present study explored the effect of divided attention on the FLE using trial-wise spatial cues to disentangle these possibilities. Previous studies have often used separate stimuli grouped as a single moving object (dots arranged in a line; Baldo & Klein, 1995; Krekelberg & Lappe, 1999) or multiple objects not grouped but having the same motion (dots revolving in a circular path; Khurana et al., 2000; Shioiri et al., 2010; for an extensive review, see Hubbard, 2014), also potentially causing grouping effects. In contrast, we employed several objects characterized by independent motion trajectories. In this novel paradigm, an array of identically looking bars was presented in different locations, and a cue preceding each trial indicated the bar to be tracked. All bars rotated, but participants were required to covertly track the moving bar in the cued quadrant(s) of the display. We varied the amount of attention available to the bar by dividing the participants' attention between other bars in one, two, three, or across four quadrants, while a target flashed next to one of the bars simultaneously. Subsequently, participants were asked to indicate the position of that bar at the time of the flash. Assuming the FLE would be present in all attention conditions, we hypothesized that the effects of divided attention would be expressed in three scenarios as increased FLE magnitude and variability ("prediction model"), increased FLE magnitude without changing the variability ("processing speed model"), or increased FLE variability without changing the magnitude ("processing quality model").

2. Materials and Methods

2.1 Participants

Twenty-six healthy participants were recruited from the Forschungszentrum Jülich. Two participants were excluded due to insufficient data quality (see **section 2.5** for details), so data from 24 participants (15 female, 9 male, age [M: 28.8 years, SD: 4 years], range 21–40 years) were included in the final analyses. This sample size was motivated by a preliminary power calculation for a desired medium effect size (Cohen's $f = 0.25$) with a power of 80% and an alpha level of 0.05 for a repeated-measures analysis of variance (ANOVA). All participants were fluent in spoken and written English (in order to understand task instructions), had normal or corrected-to-normal visual acuity, and had no neurological or psychiatric disorders. Handedness was not a selection criterion, and participants self-reported their handedness preferences (19 right-handed and 5 left-handed). All participants provided informed written consent and received compensation of 10 Euros per hour for their participation. This study was conducted following the Declaration of Helsinki and approved by the ethics committee of the German Psychological Society (DGPs) (Ethics ID: 2022-02-03VA).

2.2 Apparatus

Visual stimuli were generated using Psychopy 3.0 (Peirce, 2007, 2009) and presented on a 22-inch Samsung SyncMaster 2233RZ LCD monitor with a 1680 x 1050 pixel resolution and a refresh rate of 120 Hz (as outlined in Wang & Nikolic, 2011). A chinrest was used to stabilize the head and maintain a viewing distance of 70 cm. The center of the screen was approximately at eye level. A standard QWERTY keyboard was positioned below the chinrest and not visible from the participants' field of view, with the left hand on the space bar and the right hand on the arrow keys. The experiment was conducted in a soundproof, light-attenuated room.

2.3 Stimuli

A white fixation cross subtending 0.5° x 0.5° of visual angle (dva) was continuously displayed at the center of a black background. The spatial cue consisted of one, two, three, or four yellow dots (radius = 0.15 dva) presented at the corners of the central fixation cross. The dots indicated the quadrant(s) of the display in which the flash could occur. Every possible combination of dots was realized (e.g., for two quadrants, two dots on the left, right, upper, lower, and diagonal quadrants). The moving stimuli consisted of four gray bars, which rotated smoothly around the center of each quadrant at an angular velocity of 240°/s. Therefore, the placement of each bar was 0.13 x 6.04 dva, with its inner end at 9.98 dva eccentricity from fixation. On one end of each bar was a small dot (radius = 0.13 dva) used to indicate the bar's position, namely, relative to the position of the static stimulus. The static stimulus (target) was a red dot of the same size as the dot end (radius = 0.13 dva) and was always positioned at 0.8 dva from the bar (dot end).

2.4 Procedure

In each trial, participants were instructed to fixate on the central fixation cross for the duration of the stimulation sequence (**Figure 1A**). Attention cues were displayed for 600 ms, pointing to the quadrant(s) to be attended. The cues signaled the quadrant but not the position within the quadrant, in which the target likely appeared in the upcoming display (see below). After a 500-ms interval allowing participants to covertly orient their attention to the cued quadrant(s), an array of four rotating bars was presented surrounding the central fixation cross. The bars rotated in the same clockwise or counter-clockwise direction, randomly interwoven across trials, with the restriction that each bar had a distinct starting orientation: 0°, 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5°, 180°, 202.5°, 225°, 247.5°, 270°, 292.5°, 315°, or 337.5° from the vertical. This arrangement allowed the bars to rotate along independent motion trajectories despite their shared direction of motion. Periodically after 850, 1000, or 1150 ms chosen at random, the target briefly flashed (25 ms) next to one of the bars. After the target offset, the bars continued to rotate for an additional 1150, 1000, or 850 ms. The participants' task was to make a delayed response about the instantaneous position of the cued bar at the time of the flash, using a response probe.

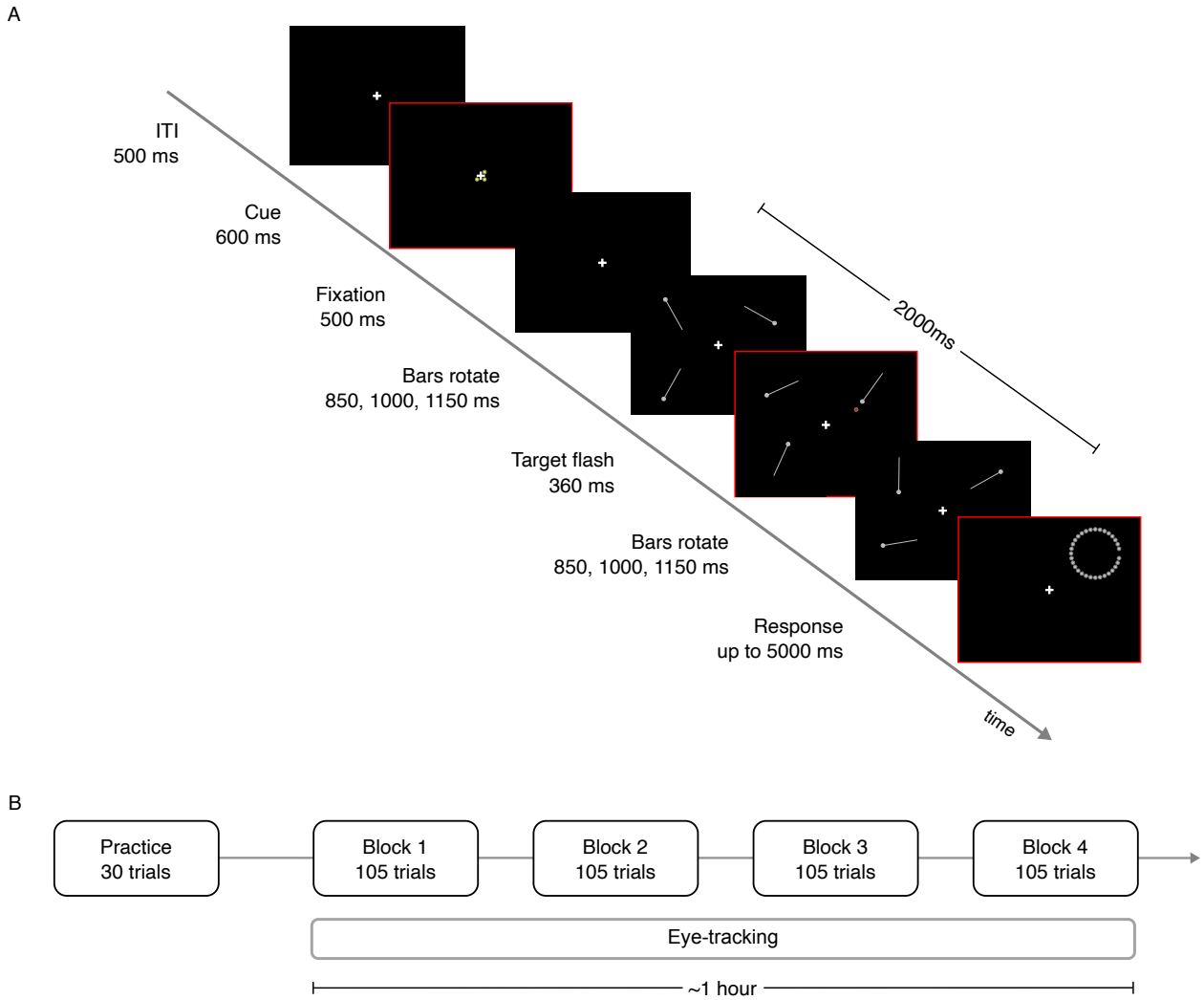

Figure 1. Experimental paradigm. (**A**) Trial sequence. Spatial cues were presented at the central fixation cross to indicate that the participants should orient their attention to the upcoming display, featuring an array of four rotating bars (not drawn to scale) in corresponding quadrants. The target flashed next to a bar at a randomly selected moment during the sequence. Here, a target is presented at a cued quadrant, but sometimes the target appeared at a non-cued quadrant (see text for details). At the end of the sequence, participants were asked to respond using a response probe. Once the participants responded, the subsequent trial began after an inter-trial interval of 500 ms. Each trial lasted up to 8 s. (**B**) Procedure timeline. Participants performed at least 30 practice trials for task familiarization, followed by four blocks of 105 trials, totaling 420 trials over approximately one hour, including eye-tracking. Each block comprised trials from all four attention conditions and every combination of cue-target configurations with equal probability. The order of trials was randomized within the block.

The response probe comprised a wheel of 60 small grey dots (each dot radius = 0.13 dva) – whose diameter was equal to the length of a bar. To perform the task, participants navigated the wheel using left and right arrow keys to select their perceived position of the bar (dot end). Once satisfied with their selection, they pressed the enter key to record the response and prompt the subsequent trial. Because the starting position on the wheel randomly varied from trial to trial, participants were instructed to respond as accurately as possible within 5000 ms. Because the target position and the corresponding bar position were always physically aligned, the participants' perceived displacement of the stimuli in the direction of motion, or lack thereof, allowed us to determine the FLE of that trial directly. This approach contrasts with the conventional method of deriving an average offset through the point of subjective equality across a block for a given condition (cf. Yook et al., 2022). The subsequent trial began after an inter-trial interval (ITI) of 500 ms.

The probe location corresponded to the quadrant in which the target was presented in the previous display, so participants did not additionally report in which quadrant they saw the target in each trial. However, the cue-target validity differed between trials. Notably, the target was presented in a cued quadrant 90% of the time. The target was presented in a non-cued quadrant on the remaining 10% of the time, and participants were asked to press the space bar and refrain from indicating the bar's position with the response probe. We refer to these trials as "catch trials", which served to ensure that participants would pay attention to the cues. If participants incorrectly responded to catch trials by responding using the probe or to a non-catch trial by pressing space, they were given feedback regarding their focus of attention: "Please pay attention to the cues as they are helpful". Otherwise, no feedback on behavioral performance was provided.

The task was divided into four blocks of 105 trials (96 non-catch trials and 9 catch trials; **Figure 1B**). This yielded a total of 420 trials over approximately one hour, with each trial lasting up to 8 s. Every combination of cue-target configurations could appear within each block with equal probability. Participants performed four attention conditions with the order of trials randomized within each block. Participants were instructed to take regular self-paced breaks between each of the four blocks and after every ~5–10 mins within each block (indicated by a break screen) to minimize fatigue.

At the beginning of the experiment, participants completed at least one block of 30 practice trials to familiarize themselves with the task. At the end of the experiment, participants were debriefed about the purpose of the study involving the FLE. None of the participants indicated that they were aware that the positions of the to-be-attended bar and target were aligned.

2.5 Data quality assessment

Data from participants who failed to identify at least 75% of catch trials were excluded from the analyses to minimize the potential impact of non-compliance with task instructions and task artifacts. This decision ensured that participants attended to the cued bar(s), as instructed. Data from two participants who detected an average of 2.5 (SD: 3.53) out of 36 catch trials throughout the experiment were excluded. Besides the catch trials, incorrectly responded non-catch trials were also excluded from further analyses. Among the remaining 24 participants who detected an average of 33.29 catch trials (SD: 2.35), an average of 379 correct non-catch trials (min: 371, max: 384, SD: 3.75) were available for analyses.

2.6 Behavioral analysis

Behavioral data were pre-processed in Anaconda 4.2.0 (Anaconda Inc., 2016) with Python 3.5 (Van Rossum & Drake, 2009) and analyzed in R Statistical Software v4.3.1 (R Core Team, 2023) with custom scripts.

Across trials, participants were required to focus on a single moving bar (focused attention condition) or simultaneously divide their attention among two, three, or four bars (divided attention conditions: attend-to-two, -three, or -four conditions). We obtained the FLE of each trial by estimating the difference between the target position and the reported bar position. Given that a value of zero indicated no difference in the positions of the two stimuli, a positive value indicated a flash-lag effect (i.e., moving bar perceived ahead of the flash). Conversely, a negative value indicated a flash-lead effect (i.e., flash perceived ahead of the moving bar).

To assess whether the magnitude of the FLE was influenced when attention was divided, we calculated the median FLE values for each condition of each participant. We then compared the means of medians (assessed per individual participant) between conditions using a one-way repeated-measures ANOVA using the ez package (Lawrence, 2016) in R. The pairwise differences between two conditions were evaluated with paired-samples *t*-tests. To correct for multiple comparisons, statistically significant differences are reported based on a threshold of $p = (0.05/n - \text{rank} + 1)$ (one-tailed), adjusted for familywise error rate (FWE) using Holm-Bonferroni correction (Holm, 1979). Greenhouse-Geisser corrections were performed when the results of Mauchly's sphericity test results were significant. The same procedure was repeated using the standard deviation to assess whether the variability of the FLE across trials was influenced by divided attention.

2.7 Eye-tracking recording and analysis

We monitored eye movements using an infrared EyeLink 1000 Plus (SR Research Ltd., Mississauga, Canada) system at a sampling rate of 1000 Hz to verify that participants maintained fixation during the stimulation sequence of each trial. The eye tracker was calibrated with a 5-point calibration procedure to establish an accurate gaze position at the beginning of the experiment. Acceptable calibration values had to meet the validation criterion of < 0.5 dva and maximum error of < 1.5 dva. The left eye's gaze positions were successfully recorded in 12 (of 24) participants due to technical problems.

Eye-tracking data were pre-processed and analyzed in R using the eyelinker package (Barthelme, 2021) and custom scripts. Fixations and saccades were determined from the raw gaze position data using Eyelink's default event parser. A fixation was defined as an event lasting at least 100 ms within a 1-dva threshold from central fixation. Saccades were identified using a velocity threshold of 30°/s and acceleration threshold of $8000°/s^2$. We applied a drift correction by subtracting the mean gaze position measured during the 500-ms ITI before the cue onset of each trial from all gaze positions of that trial to account for potential gaze position drifts. This approach ensured sensitivity to changes in head/eye position. Eye-blink events were excluded.

For each saccade, we examined the distance from a pre-determined region considered as acceptable fixation within a 2-dva threshold at any point while the stimulus was on screen (i.e. closer to stimulus position than central fixation). This analysis was conducted during three distinct time intervals of interest: during the cue presentation lasting 600 ms, immediately after the cue offset for a duration of 500 ms, and before and after the target presentation, with a combined duration of 2000 ms. During these time windows, participants were instructed to maintain fixation. By contrast, participants were allowed to make eye movements freely during the response interval. Therefore, we assessed whether participants' perceptions of the bar position were systematically influenced by voluntary eye movements, if any, during the critical time windows. The mean deviations from fixation were compared between conditions using a two-way repeated-measures ANOVA.

3. Results

3.1 Fixation controlled under all attention conditions

We compared gaze positions between conditions to ensure that overt attentional shifts did not influence the participants' report of the bar position. Across the three windows of interest (during the cue, after the cue, and before and after the target onset of each trial), there was no detectable influence of our attention manipulations in deviations from fixation (two-way ANOVA, *attention*timeWindow*: $F(6, 66) = 0.48$, $p = 0.82$; *attention*: $F(3, 33) = 0.38$, $p = 0.8$; *timeWindow*: $F(2, 22) = 36.33$, $p < 0.001$).

3.2 Attentional modulation of FLE magnitude, but not FLE variability

Figure 2A shows the FLE magnitude, expressed as the average of individual medians, in relation to the number of to-be-attended moving bars. The illusion manifested prominently across all attention conditions, ranging between 15-20° (see **Appendix A**). Notably, the mean FLE magnitude was significantly larger in divided attention conditions than in the condition where attention was focused on a single bar (one-way ANOVA, *attention*: $F(3, 69) = 9.21$, $p < 0.001$).

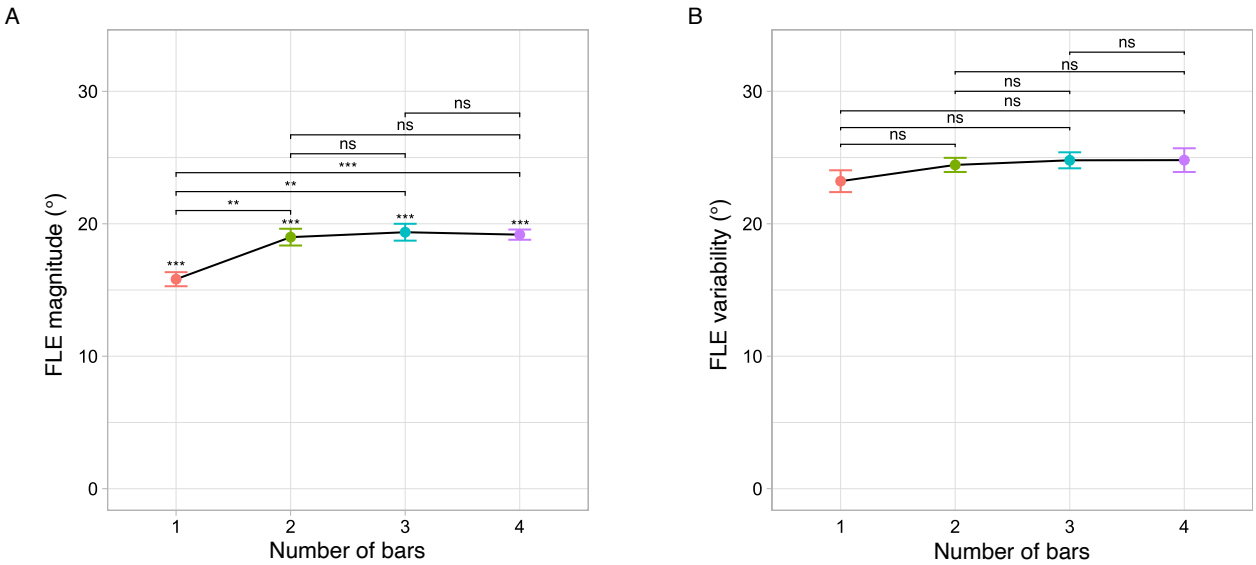

Figure 2. FLE results. (**A**) The mean FLE magnitude is plotted as a function of number of attended moving bars. All values are reported as means ± within-subject standard error of the mean (S.E.M.,

error bars). ns (not significant) denotes $p > 0.05$, ** denotes $p < 0.01$, *** denotes $p < 0.001$. (**B**) The same described in **A** but for FLE variability.

A qualitatively similar pattern was observed for the FLE variability shown in **Figure 2B** (see also **Appendix B**) but with no significant effect of attention (one-way ANOVA, *attention*: $F(3, 69) = 1.059$, $p = 0.3$) (**Table 1**).

Table 1.

Results of paired-sample *t*-tests (one-tailed) with correction for multiple comparisons for mean FLE magnitude and variability.

Pair	FLE Magnitude		FLE Variability	
	t_{23}	p	t_{23}	p
1 vs 2	-3.86	< 0.01	-1.44	0.825
1 vs 3	-4.31	0.001	-1.57	0.774
1 vs 4	-5.19	< 0.001	-1.15	1
2 vs 3	-0.38	1	-0.43	1
2 vs 4	-0.27	1	-0.35	1
3 vs 4	0.26	1	-0.01	1

4. Discussion

In this study, we measured the perceived position of the moving object during the FLE across different attention conditions. When attention was distributed across multiple quadrants of the display, we found that FLE magnitude was more significant than when attention was directed to a single quadrant, which is in line with the prediction of the processing speed model. While the prediction model and the processing quality model predicted changes in variability, the observed variability of the FLE did not differ across conditions.

In each trial, participants viewed an array of four independently moving objects in corresponding quadrants of the display. Using spatial cues, we manipulated the allocation of attention to a single object, comparing the FLE under conditions where attention was either focused or divided. This approach was accompanied by catch trials, ensuring that participants accurately directed their attention according to the provided cues. The FLE was stronger when attention was divided among multiple objects, which is consistent with previous studies (Namba & Baldo, 2004; Sarich et al., 2007; Shioiri et al., 2010; but see Khurana et al., 2000), with our study benefiting from a larger sample size (N = 24) and a trial-wise measure of the FLE.

Subtle differences emerged within conditions of divided attention – specifically, when attention was distributed among two, three, or four moving objects. While there was a notable increase in FLE magnitude when attention shifted from one to two objects, subsequent increases were qualitatively smaller and did not reach statistical significance when attention was divided among three or four objects. These findings align with Shioiri et al. (2010), who observed a similar pattern in cued conditions where up to six dots formed a circle rather than being neatly arranged in single quadrants. Interestingly, Hogendoorn et al. (2010) presented a comparable set-up where attention was divided among six clocks in a circle; however, they observed an opposite pattern, with a gradual increase in magnitude (measured as time) from one to six clocks and a step-wise increase in variability from one to two clocks, but not beyond.

Our attentional manipulation may have peaked in the attend-to-two condition, and further dividing attention was less impactful in the FLE, indicating a saturation effect under highly divided-

attention conditions (Howe & Holcombe, 2012; Luu & Howe, 2015). According to Shioiri et al., this saturation effect could be related to the spatial spread of attention, independent of the number of attended objects. For example, Khurana et al.'s (2000) study involved two moving objects above and below the fixation point. Therefore, their cues indicated one of two possible locations where the flash could appear, resulting in no difference in FLE magnitude (although in response time; see **Appendix D**). Given that our study was similarly limited to four moving objects in four quadrants, this pattern of results is coherent. Under these conditions, attention effects may not necessarily follow a linear pattern but may critically depend on task demands (Khurana et al., 2000; Shioiri et al., 2010). However, there is some evidence that attentional resources may be hemifield-limited (Alvarez & Cavanagh, 2005; Luck et al., 1989) or even quadrant-limited (Carlson et al., 2007, 2011). If each quadrant has discrete attentional capacity, then dividing attention would not impact tracking additional moving objects in extra quadrants. This explanation could account for the deviation observed in our supplementary analysis exploring FLE anisotropy (see **Appendix C**) and the discrepancy in Khurana et al. (2000), showing no attention modulation compared to other studies.

A promising avenue for future research involves increasing the demand for top-down attention to address the observed saturation effect. It is possible that the current experiment set-up was too easy. This draw-back could be addressed by manipulating attentional load, such as varying the number of stimuli (> 1) in each quadrant across the four quadrants or varying eccentricities from each other (Baldo et al., 2002). Additionally, motion speed has been reported to influence the attention modulation in the FLE (Shioiri et al., 2010). Selectively manipulating the speed of moving stimuli within this paradigm could further reveal whether more attention is required to track faster motion, potentially influencing the FLE to a greater extent than observed here.

The results of the current study show a similar pattern as those reported by Namba and Baldo (2004), Sarich et al. (2007), and Shioiri et al. (2010). However, since these studies did not employ catch trials as done here, their results could be explained by anticipatory processing of the flash (Baldo & Klein, 1995; Khurana et al., 2000; Namba & Baldo, 2004; Shioiri et al., 2010). According to this interpretation, attention facilitates the processing of the flash (Baldo et al., 2002; Vreven & Verghese, 2005), reducing the latency difference between the static flash and the moving object

under focused attention conditions (Shioiri et al., 2010). Conversely, under divided attention conditions, the latency difference for each object may increase, potentially leading to a larger perceived offset between the two (Öğmen et al., 2004; Purushothaman et al., 1998; Whitney & Cavanagh, 2000; Whitney & Murakami, 1998). Although it is difficult to definitively rule out attention's influence on the flash, it seems implausible that the flash's impact can solely explain our results. While this interpretation would also hypothesize larger FLE magnitudes when attention is divided among multiple objects, it implies that participants might anticipate the occurrence of the flash even without explicit cues. The inclusion of catch trials in our analysis reduces the likelihood that participants were just waiting to detect the flash. Instead, the catch trials added a control measure to validate the effectiveness of the cues. If participants were waiting to detect the flash, then they would be expected to report the FLE on these trials, rendering the cues ineffective. However, our data indicate that participants did notice when the flash was presented next to a non-cued bar, suggesting that they did not merely wait for the flash on each trial.

Besides, as our analysis focused on non-catch trials, another valuable avenue for future research could involve measuring the FLE on catch trials. Increasing the frequency of catch trials as a control condition would be advantageous for a more comprehensive investigation. A lack of discernable difference in FLE magnitudes between catch and non-catch trials would strongly indicate that observed FLE changes were solely driven by the flash. This would provide further insights into how attention influences the perception of motion rather than the detection of the flash. Additionally, our investigation of the FLE led us to consider another motion-induced position shift known as the representational momentum (RM; Freyd & Finke, 1984; Hubbard, 1995). Unlike the FLE, RM illustrates a perceived forward shift of a moving object's stopping position, reflecting prediction about its motion trajectory without comparing it with another stimulus. However, like the FLE, RM has been reported to observe similar modulations due to attention (Hayes & Freyd, 2002; Hubbard et al., 2009; for reviews, see Hubbard, 2005, 2013, 2018), suggesting that a common extrapolation mechanism might underlie the attentional modulation in these illusions (but see White, 2018).

Our current results and previous findings consistently demonstrate larger FLE magnitudes under divided attention conditions and smaller FLE magnitudes with focused attention. If we interpret

the FLE as a consequence of motion extrapolation, this pattern could be explained by two potential mechanisms: attention modulates the impact of neural processing latencies or influences reliance on predictive processing. Here, we speculated that divided attention may give rise to existing predictions rather than wait for slow sensory input. However, the data do not seem to support the possibility that divided attention enhances prediction itself since FLE variability did not modulate with the presence of multiple simultaneously moving objects. Instead, our results are more in accord with the view of an attentional effect on processing latencies, thereby modulating the degree of compensatory motion extrapolation.

Conclusions

In conclusion, the experiment reported here is the first to manipulate attention in the flash-lag paradigm using a combination of conventional attentional cueing and divided attention procedures with trial-wise FLE readouts. Our results contribute to the growing body of evidence demonstrating that for the brain to partly overcome its delays and allow us to interact with dynamic stimuli without significant delays, it must always predict the future. More specifically, our results reveal a dependency of these compensatory mechanisms on attention in dynamic environments. Attention is crucial in efficiently processing multiple moving objects and facilitates motion extrapolation.

Acknowledgements

We thank our colleagues of the INM-3 for their valuable discussions and support.

Commercial relationships: none

Corresponding author: Simone Vossel
Email: s.vossel@fz-juelich.de
Address: Cognitive Neuroscience, Institute of Neuroscience and Medicine (INM-3), Forschungszentrum Jülich, 52428 Jülich, Germany

Appendices for

When visual attention is divided in the flash-lag effect

Jane Yook *et al*.

Appendix A: Above-zero flash-lag effect (FLE) magnitude

Table A1.

Results of one-sample *t*-tests (one-tailed) for mean FLE magnitude.

Bars	*M*	*SD*	t_{23}	*p*
1	15.82°	6.4°	12.11	< 0.001
2	18.99°	9.01°	10.33	< 0.001
3	19.36°	6.5°	14.61	< 0.001
4	19.18°	7.22°	13.01	< 0.001

Appendix B: Descriptive statistics for FLE variability

Table B1.

Descriptive statistics for mean FLE variability across attention conditions.

Bars	*M*	*SD*
1	23.22°	14.65°
2	24.44°	14.72°
3	24.79°	12.78°
4	24.81°	14.96°

Appendix C: Hemifield effects in the FLE

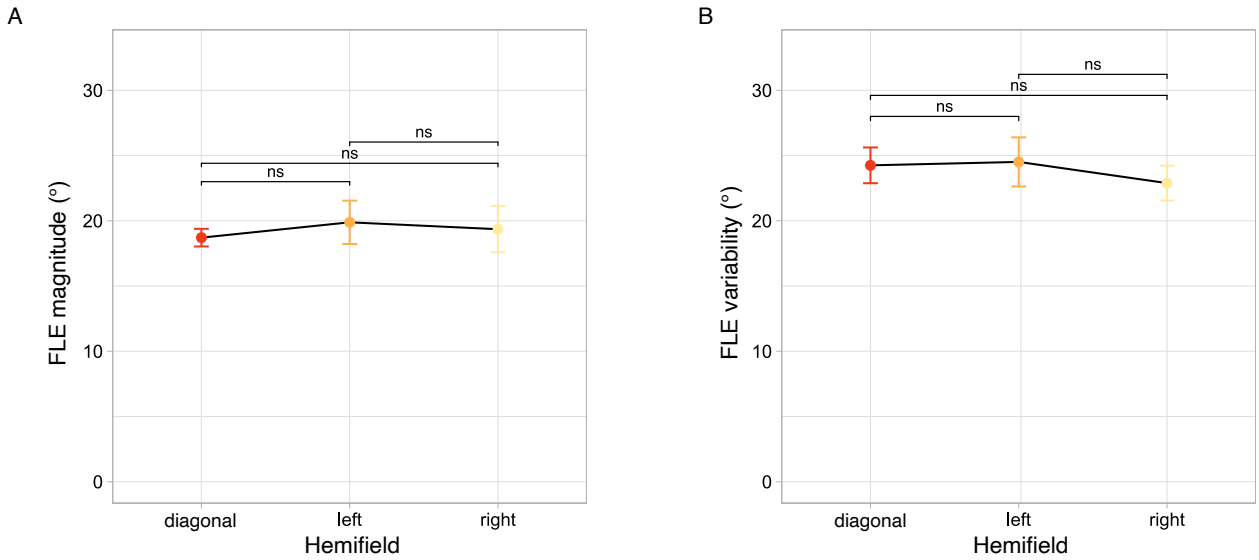

Figure C1. Hemifield results. We investigated the attentional modulation of the FLE, focusing on where attention was allocated. Using linear motion, previous studies have demonstrated an FLE asymmetry in the left and right sides of the visual field (Kanai et al., 2004; Shi & Nijhawan, 2008; Suzuki et al., 2023). Notably, the FLE tends to be more substantial when stimuli are presented in the left hemifield. Therefore, we aimed to test whether the effects of divided attention were more pronounced with FLE anisotropy, particularly within the attend-to-two condition. To this end, we examined the magnitude and variability of the FLE when participants were cued to two quadrants within their left hemifield, right hemifield, or diagonally across the upper and lower visual hemifields. (**A**) The mean FLE magnitude is plotted as a function of the attended hemifields. All values are reported as means ± within-subject standard error of the mean (S.E.M., error bars). ns (not significant) denotes $p > 0.05$. Although the FLE magnitude in the left hemifield was marginally higher than in the right or diagonal hemifields (**Table S3**), no significant modulation of attention was detected (one-way ANOVA, *hemiField:* $F(2,46) = 0.16$, $p = 0.741$). (**B**) The same as described in **A** but for mean FLE variability based on the oriented attention across hemifields (one-way ANOVA, *hemiField:* $F(2,46) = 0.32$, $p = 0.73$).

Table C2.

Results of the paired-sample *t*-tests (two-tailed) with Bonferroni correction for multiple comparisons for mean FLE magnitude and variability.

Pair	FLE Magnitude		FLE Variability	
	t_{23}	p	t_{23}	p
left vs right	0.19	1	0.67	1
diagonal vs left	-0.79	1	-0.11	1
diagonal vs right	-0.38	1	0.86	1

Appendix D: Response times

While response time (RT) is commonly utilized as an indicator of faster processing in the literature (see also Khurana et al., 2000), our study primarily focused on assessing the magnitude and variability of the FLE. There were two key reasons for not analyzing RTs in this paradigm. Firstly, our experimental task deliberately emphasized response accuracy (i.e., the bar position) over speed in determining the FLE. Unlike the emphasis on speed in previous studies such as Khurana et al. (2000), our goal was to ensure accuracy in the FLE task. Secondly, the starting position on the response probe introduced inherent variability. Longer response times were needed when the distance from the starting position to the desired position was greater. The focus of our study was the magnitude and variability of the FLE, and the RT analysis was not aligned with our primary research questions.

The RTs from the onset of the response probe averaged approximately ~3400 ms across all conditions (**Table D1**).

Table D1.

Descriptive statistics for mean RTs across attention conditions.

Bars	*M*	*SD*
1	3438 ms	133 ms
2	3450 ms	135 ms
3	3435 ms	135 ms
4	3439 ms	138 ms

References

Adamian, N., & Andersen, S. K. (2022). Attentional Enhancement of Tracked Stimuli in Early Visual Cortex Has Limited Capacity. *The Journal of Neuroscience*, *42*(46), 8709–8715. https://doi.org/10.1523/JNEUROSCI.0605-22.2022

Alvarez, G. A., & Cavanagh, P. (2005). Independent Resources for Attentional Tracking in the Left and Right Visual Hemifields. *Psychological Science*, *16*(8), 637–643. https://doi.org/10.1111/j.1467-9280.2005.01587.x

Anaconda Inc. (2016). *Anaconda Software Distribution* (Version 2-2.4.0). Anaconda Inc. Austin, TX, USA. https://www.anaconda.com/

Anton-Erxleben, K., & Carrasco, M. (2013). Attentional enhancement of spatial resolution: Linking behavioural and neurophysiological evidence. *Nature Reviews. Neuroscience*, *14*(3), 188–200. https://doi.org/10.1038/nrn3443

Baldo, M. V. C., Kihara, A. H., Namba, J., & Klein, S. A. (2002). Evidence for an Attentional Component of the Perceptual Misalignment between Moving and Flashing Stimuli. *Perception*, *31*(1), 17–30. https://doi.org/10.1068/p3302

Baldo, M. V. C., & Klein, S. A. (1995). Extrapolation or attention shift? *Nature*, *378*(6557), Article 6557. https://doi.org/10.1038/378565a0

Baldo, M. V. C., & Klein, S. A. (2010). Paying attention to the flash-lag effect. In R. Nijhawan & B. Khurana (Eds.), *Space and Time in Perception and Action* (1st ed., pp. 396–407). Cambridge University Press. https://doi.org/10.1017/CBO9780511750540.023

Barbot, A., & Carrasco, M. (2017). Attention Modifies Spatial Resolution According to Task Demands. *Psychological Science*, *28*(3), 285–296. https://doi.org/10.1177/0956797616679634

Barthelme, S. (2021). *eyelinker: Import ASC Files from EyeLink Eye Trackers.* R package version 0.2.1. https://cran.r-project.org/web/packages/eyelinker/index.html

Brenner, E., & Smeets, J. B. J. (2000). Motion extrapolation is not responsible for the flash–lag effect. *Vision Research*, *40*(13), 1645–1648. https://doi.org/10.1016/S0042-6989(00)00067-5

Carlson, T. A., Alvarez, G. A., & Cavanagh, P. (2007). Quadrantic deficit reveals anatomical constraints on selection. *Proceedings of the National Academy of Sciences*, *104*(33), 13496–13500. https://doi.org/10.1073/pnas.0702685104

Carlson, T. A., Cho, H., Turret, J., & Dakin, S. (2011). Psychoanatomy of visual attention: A unified account of quadrant and hemifield effects. *Journal of Vision*, *11*(11), 101–101. https://doi.org/10.1167/11.11.101

Carrasco, M., & McElree, B. (2001). Covert attention accelerates the rate of visual information processing. *Proceedings of the National Academy of Sciences*, *98*(9), 5363–5367. https://doi.org/10.1073/pnas.081074098

Eagleman, D. M., & Sejnowski, T. J. (2000). Motion Integration and Postdiction in Visual Awareness. *Science*, *287*(5460), 2036–2038. https://doi.org/10.1126/science.287.5460.2036

Freyd, J. J., & Finke, R. A. (1984). Representational momentum. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *10*(1), 126–132. https://doi.org/10.1037/0278-7393.10.1.126

Giordano, A. M., McElree, B., & Carrasco, M. (2009). On the automaticity and flexibility of covert attention: A speed-accuracy trade-off analysis. *Journal of Vision*, *9*(3), 30. https://doi.org/10.1167/9.3.30

Hayes, A. E., & Freyd, J. J. (2002). Representational momentum when attention is divided. *Visual Cognition*, *9*(1–2), 8–27. https://doi.org/10.1080/13506280143000296

Hogendoorn, H., Carlson, T. A., Vanrullen, R., & Verstraten, F. A. J. (2010). Timing divided attention. *Attention, Perception, & Psychophysics*, *72*(8), 2059–2068. https://doi.org/10.3758/BF03196683

Holm, S. (1979). A Simple Sequentially Rejective Multiple Test Procedure. *Scandinavian Journal of Statistics*, *6*(2), 65–70.

Howe, P. D. L., & Holcombe, A. O. (2012). Motion information is sometimes used as an aid to the visual tracking of objects. *Journal of Vision*, *12*(13), 10–10. https://doi.org/10.1167/12.13.10

Hubbard, T. L. (1995). Environmental invariants in the representation of motion: Implied dynamics and representational momentum, gravity, friction, and centripetal force. *Psychonomic Bulletin & Review*, *2*(3), 322–338. https://doi.org/10.3758/BF03210971

Hubbard, T. L. (2005). Representational momentum and related displacements in spatial memory: A review of the findings. *Psychonomic Bulletin & Review*, *12*(5), 822–851. https://doi.org/10.3758/BF03196775

Hubbard, T. L. (2013). Do the flash-lag effect and representational momentum involve similar extrapolations? *Frontiers in Psychology*, *4*. https://doi.org/10.3389/fpsyg.2013.00290

Hubbard, T. L. (2014). The flash-lag effect and related mislocalizations: Findings, properties, and theories. *Psychological Bulletin*, *140*(1), 308–338. https://doi.org/10.1037/a0032899

Hubbard, T. L. (2018). Influences on representational momentum. In *Spatial biases in perception and cognition* (pp. 121–138). Cambridge University Press. https://doi.org/10.1017/9781316651247.009

Hubbard, T. L., Kumar, A. M., & Carp, C. L. (2009). Effects of spatial cueing on representational momentum. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(3), 666–677. https://doi.org/10.1037/a0014870

Johnson, P. A., Blom, T., Van Gaal, S., Feuerriegel, D., Bode, S., & Hogendoorn, H. (2023). Position representations of moving objects align with real-time position in the early visual response. *eLife*, *12*, e82424. https://doi.org/10.7554/eLife.82424

Kanai, R., Sheth, B. R., & Shimojo, S. (2004). Stopping the motion and sleuthing the flash-lag effect: Spatial uncertainty is the key to perceptual mislocalization. *Vision Research*, *44*(22), 2605–2619. https://doi.org/10.1016/j.visres.2003.10.028

Khurana, B., Watanabe, K., & Nijhawan, R. (2000). The Role of Attention in Motion Extrapolation: Are Moving Objects 'Corrected' or Flashed Objects Attentionally Delayed? *Perception*, *29*(6), 675–692. https://doi.org/10.1068/p3066

Krekelberg, B., & Lappe, M. (1999). Temporal recruitment along the trajectory of moving objects and the perception of position. *Vision Research*, *39*(16), 2669–2679. https://doi.org/10.1016/S0042-6989(98)00287-9

Krekelberg, B., & Lappe, M. (2001). Neuronal latencies and the position of moving objects. *Trends in Neurosciences*, *24*(6), 335–339. https://doi.org/10.1016/S0166-2236(00)01795-1

Lappe, M., & Krekelberg, B. (1998). The Position of Moving Objects. *Perception*, *27*(12), 1437–1449. https://doi.org/10.1068/p271437

Lawrence, M. (2016). *ez: Easy Analysis and Visualization of Factorial Experiments.* R package version 4.4-0. https://CRAN.R-project.org/package=ez

Luck, S. J., Hillyard, S. A., Mangun, G. R., & Gazzaniga, M. S. (1989). Independent hemispheric attentional systems mediate visual search in split-brain patients. *Nature*, *342*(6249), 543–545. https://doi.org/10.1038/342543a0

Luu, T., & Howe, P. D. L. (2015). Extrapolation occurs in multiple object tracking when eye movements are controlled. *Attention, Perception, & Psychophysics*, *77*(6), 1919–1929. https://doi.org/10.3758/s13414-015-0891-8

Mackay, D. M. (1958). Perceptual Stability of a Stroboscopically Lit Visual Field containing Self-Luminous Objects. *Nature*, *181*(4607), 507–508. https://doi.org/10.1038/181507a0

Murakami, I. (2001). The flash-lag effect as a spatiotemporal correlation structure. *Journal of Vision*, *1*(2), 6. https://doi.org/10.1167/1.2.6

Namba, J., & Baldo, M. V. C. (2004). The Modulation of the Flash-Lag Effect by Voluntary Attention. *Perception*, *33*(5), 621–631. https://doi.org/10.1068/p5212

Nijhawan, R. (2002). Neural delays, visual motion and the flash-lag effect. *Trends in Cognitive Sciences*, *6*(9), 387–393. https://doi.org/10.1016/S1364-6613(02)01963-0

Nijhawan, R. (2008). Visual prediction: Psychophysics and neurophysiology of compensation for time delays. *Behavioral and Brain Sciences*, *31*(2), 179–198. https://doi.org/10.1017/S0140525X08003804

Norman, D. A., & Bobrow, D. G. (1975). On data-limited and resource-limited processes. *Cognitive Psychology*, *7*(1), 44–64. https://doi.org/10.1016/0010-0285(75)90004-3

Öğmen, H., Patel, S. S., Bedell, H. E., & Camuz, K. (2004). Differential latencies and the dynamics of the position computation process for moving targets, assessed with the flash-lag effect. *Vision Research*, *44*(18), 2109–2128. https://doi.org/10.1016/j.visres.2004.04.003

Peirce, J. W. (2007). PsychoPy—Psychophysics software in Python. *Journal of Neuroscience Methods*, *162*(1), 8–13. https://doi.org/10.1016/j.jneumeth.2006.11.017

Peirce, J. W. (2009). Generating stimuli for neuroscience using PsychoPy. *Frontiers in Neuroinformatics*, *2*. https://www.frontiersin.org/articles/10.3389/neuro.11.010.2008

Posner, M. I. (1980). Orienting of attention. *The Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. https://doi.org/10.1080/00335558008248231

Purushothaman, G., Patel, S. S., Bedell, H. E., & Ogmen, H. (1998). Moving ahead through differential visual latency. *Nature*, *396*(6710), 424–424. https://doi.org/10.1038/24766

Pylyshyn, Z. W., & Storm, R. W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision*, *3*(3), 179–197. https://doi.org/10.1163/156856888x00122

R Core Team. (2023). *R: A Language and Environment for Statistical Computing.* Vienna, Austra. R Foundation for Statistical Computing. https://www.r-project.org/

Reynolds, J. H., & Chelazzi, L. (2004). Attentional modulation of visual processing. *Annual Review of Neuroscience*, *27*(1), 611–647. https://doi.org/10.1146/annurev.neuro.26.041002.131039

Sarich, D., Chappell, M., & Burgess, C. (2007). Dividing attention in the flash-lag illusion. *Vision Research*, *47*(4), 544–547. https://doi.org/10.1016/j.visres.2006.09.029

Schneider, K. A. (2018). The Flash-Lag, Fröhlich and Related Motion Illusions Are Natural Consequences of Discrete Sampling in the Visual System. *Frontiers in Psychology*, *9*, 1227. https://doi.org/10.3389/fpsyg.2018.01227

Shi, Z., & Nijhawan, R. (2008). Behavioral significance of motion direction causes anisotropic flash-lag, flash-drag, flash-repulsion, and movement-mislocalization effects. *Journal of Vision*, *8*(7), 24. https://doi.org/10.1167/8.7.24

Shioiri, S., Yamamoto, K., Oshida, H., Matsubara, K., & Yaguchi, H. (2010). Measuring attention using flash-lag effect. *Journal of Vision*, *10*(10), 10–10. https://doi.org/10.1167/10.10.10

Summerfield, C., & Egner, T. (2009). Expectation (and attention) in visual cognition. *Trends in Cognitive Sciences*, *13*(9), 403–409. https://doi.org/10.1016/j.tics.2009.06.003

Suzuki, Y., Atmaca, S., & Laeng, B. (2023). The lateralized flash-lag illusion: A psychophysical and pupillometry study. *Brain and Cognition*, *166*, 105956. https://doi.org/10.1016/j.bandc.2023.105956

Van Rossum, G., & Drake, F. L. (2009). *Python 3 Reference Manual*. Scotts Valley, CA: CreateSpace.

Vreven, D., & Verghese, P. (2005). Predictability and the Dynamics of Position Processing in the Flash-Lag Effect. *Perception*, *34*(1), 31–44. https://doi.org/10.1068/p5371

Wang, P., & Nikolic, D. (2011). An LCD Monitor with Sufficiently Precise Timing for Research in Vision. *Frontiers in Human Neuroscience*, *5*. https://www.frontiersin.org/articles/10.3389/fnhum.2011.00085

Whitney, D., & Cavanagh, P. (2000). Motion distorts visual space: Shifting the perceived position of remote stationary objects. *Nature Neuroscience*, *3*(9), 954–959. https://doi.org/10.1038/78878

Whitney, D., & Murakami, I. (1998). Latency difference, not spatial extrapolation. *Nature Neuroscience*, *1*(8), 656–657. https://doi.org/10.1038/3659

Yeshurun, Y., & Carrasco, M. (1998). Attention improves or impairs visual performance by enhancing spatial resolution. *Nature*, *396*(6706), Article 6706. https://doi.org/10.1038/23936

Yeshurun, Y., & Carrasco, M. (1999). Spatial attention improves performance in spatial resolution tasks1Parts of this study were presented at the Annual Meeting of the Association for Research in Vision and Ophthalmology (May 1997) and at the Annual Meeting of the Psychonomics Society (November 1997) and published in Abstract format (Yeshurun and Carrasco, 1997and Carrasco and Yeshurun, 1997, respectively).1. *Vision Research*, *39*(2), 293–306. https://doi.org/10.1016/S0042-6989(98)00114-X

Yook, J., Lee, L., Vossel, S., Weidner, R., & Hogendoorn, H. (2022). Motion extrapolation in the flash-lag effect depends on perceived, rather than physical speed. *Vision Research*, *193*, 107978. https://doi.org/10.1016/j.visres.2021.107978