When visual attention is divided in the flash-lag effect

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The flash-lag effect (FLE) occurs when a flash's position seems to be delayed relative to a continuously moving object, even though both are physically aligned. Although several studies have demonstrated that reduced attention increases FLE magnitude, the precise mechanism underlying these attention-dependent effects remains elusive. In this study, we investigated the influence of visual attention on the FLE by manipulating the level of attention allocated to multiple stimuli moving simultaneously in different locations. Participants were cued to either focus on one moving stimulus or split their attention among two, three, or four moving stimuli presented in different quadrants. We measured trial-wise FLE to explore potential changes in the magnitude of perceived displacement and its trial-to-trial variability under different attention conditions. Our results reveal that FLE magnitudes were significantly greater when attention was divided among multiple stimuli compared with when attention was focused on a single stimulus, suggesting that divided attention considerably augments the perceptual illusion. However, FLE variability, measured as the coefficient of variation, did not differ between conditions, indicating that the consistency of the illusion is unaffected by divided attention. We discuss the interpretations and implications of our findings in the context of widely accepted explanations of the FLE within a dynamic environment.

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Introduction

Attention is crucial in how we process and represent information in our visual environment. For dynamic information, attention may be essential for updating and maintaining coherent representations of moving objects (Iordanescu, Grabowecky, & Suzuki, 2009; Kerzel, 2003). When attention is limited, however, perceptual biases and illusions, such as the displacement in an object's position owing to its motion or the motion of other objects, can be significantly altered.

One such illusion is the flash-lag effect (FLE). The FLE occurs when a static flash appears 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 (Nijhawan, 1994). Specifically, the flash is misperceived as lagging behind the moving object. Although several studies have demonstrated that the allocation of attention modulates the magnitude of the FLE, the precise mechanism underlying such attention-dependent effects remains elusive. Additionally, the relationship between attention and (in)variability of moving objects' perceived positions is not well-understood.

Sarich, Chappell, and Burgess (2007) used 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 required simultaneous attention, the magnitude of the FLE increased, and detection worsened. This complements observations regarding the phenomenon of representational momentum (Freyd & Finke, 1984), where the perceived final position of a moving object is shifted forward in the direction of anticipated motion and increases with divided attention (Hayes & Freyd, 2002).

Shioiri, Yamamoto, Oshida, Matsubara, and Yaguchi (2010) manipulated attention by varying the number of moving stimuli and presenting the flash next to one of these stimuli. They observed an increase in the FLE when attention was divided among two or six stimuli and a decrease when attention was focused solely on one stimulus. Conversely, when participants were pre-cued to the upcoming locations of either the moving object or the flash, the FLE reduced following valid cues compared with invalid (Baldo & Klein, 2010; Namba & Baldo, 2004; Vreven & Verghese, 2005; but see Khurana, Watanabe, & Nijhawan, 2000) or no cues (Shioiri et al., 2010). This pattern was also reported regarding representational momentum (Hubbard, Kumar, & Carp, 2009).

However, in tasks involving multiple object tracking (Pylyshyn & Storm, 1988), which requires precise localization of targets among other moving objects, divided attention has been shown to increase errors in extrapolating predictable motion trajectories (Adamian & Andersen, 2022; Howe & Holcombe, 2012; Luu & Howe, 2015; Zhong et al., 2014). These varying effects of reduced attention across different illusions and paradigms underscore the complexity of how attention influences the representation of moving objects and the need to disentangle the specific mechanisms underlying these effects. Therefore, the present study investigated whether attention not only influences the strength of perceptual illusions like the FLE but also affects the quality of representation, such as spatial resolution (Anton-Erxleben & Carrasco, 2013; Barbot & Carrasco, 2017; Yeshurun & Carrasco, 1998; Yeshurun & Carrasco, 1999).

To this end, we examined whether divided attention affects the magnitude or the trial-to-trial variability of the FLE using trial-wise spatial cues. Previous studies often used stimuli grouped as a single moving object (e.g., dots arranged in a line) (Baldo & Klein, 1995; Krekelberg & Lappe, 1999) or multiple objects following the same motion trajectory (e.g., dots revolving in a circular path) (Khurana et al., 2000; Shioiri et al., 2010), which could introduce grouping effects. In contrast, our study used objects characterized by independent motion trajectories to minimize such effects.

In our novel experimental paradigm, participants viewed an array of identically appearing bars presented in different locations. A cue preceding each trial indicated which bar(s) participants should track. Although all bars rotated simultaneously, participants were required to covertly track the moving bar in the cued quadrant(s) of the display. Importantly, the perceptual configuration remained the same whether attention was focused on a single bar or divided across two, three, or four bars. During each trial, a target flash was presented next to one of the bars, and participants were instructed to indicate the position of the corresponding bar at the time of the flash. We compared the effects of divided attention to focused attention on both FLE magnitude and consistency (trial-to-trial variability of the FLE).

Methods

Participants

Twenty-six healthy adults were recruited from the Forschungszentrum Jülich to participate in the experiment. Two participants were excluded owing to insufficient data quality (see the Data quality assessment section for details), resulting in data from

24 participants (15 female, 9 male; mean age, 28.8 ± 4 years; range 21–40 years) being included in the final analysis. The sample size was determined 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, had normal or corrected-to-normal visual acuity, and had no neurological or psychiatric disorders. Handedness was not a selection criterion; participants self-reported their handedness preferences (19 right handed, 5 left handed). All participants provided informed written consent and received compensation of 10 Euros per hour for their participation. This study was conducted in accordance with the Declaration of Helsinki and approved by the ethics committee of the German Psychological Society (DGPs) (Ethics ID: 2022-02-03VA).

Apparatus

Visual stimuli were generated using Psychopy 3.0 (Peirce, 2007; Peirce, 2009) and presented on a 22-inch Samsung SyncMaster 2233RZ LCD monitor with a resolution of 1,680 × 1,050 pixels 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, with the center of the screen 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.

Stimuli

A white fixation cross, subtending 0.5° × 0.5° of visual angle (dva), was displayed continuously 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, indicating the quadrant(s) where the target flash could occur. Every possible combination of dots was realized (e.g., for two quadrants, two dots on the left, right, upper, lower, or diagonal quadrants).

The moving stimuli consisted of four gray bars, each rotating smoothly around the center of its respective quadrant at an angular velocity of 240°/s. Each bar measured 0.13 × 6.04 dva, with its inner end positioned at 9.98 dva from the central fixation. On one end of each bar was a small dot (radius = 0.13 dva) used to indicate the bar's position relative to the target flash. The target was a red dot of the same size (radius = 0.13 dva) and was always positioned at 0.8 dva from the bar's dot end.

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. These cues pointed to the quadrant but not the specific position within the quadrant where the target was likely to appear in the upcoming display.

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 around the central fixation cross. The bars rotated in either a clockwise or counter-clockwise direction, alternating randomly across trials. Each bar started from a unique orientation, chosen from 1 of 16 uniformly distributed orientations. This configuration allowed the bars to rotate along independent motion trajectories despite their shared direction of motion.

Periodically after 850, 1,000, or 1,150 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 1,150, 1,000, or 850 ms (for a total duration of 2,000 ms). Participants' task was to indicate the instantaneous position of the cued bar at the time of the flash on a circular response probe.

The response probe comprised a ring 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 ring using the left and right arrow keys to select their perceived position of the bar's dot end displayed on the ring.

The starting position on the ring randomly varied from trial to trial, which introduced an inherent variability in how quickly participants could accurately respond, resulting in longer response times when the distance from the desired position was greater. Although response time is a common measure in similar paradigms (see Khurana et al., 2000), we did not analyze response times for the current experiment. Instead, participants were instructed to respond within a 5,000-ms window, focusing on accuracy rather than speed. A response was registered when the enter key was pressed. The subsequent trial began after an inter-trial interval of 500 ms.

Importantly, because the target and its corresponding bar were presented in alignment, the perceived displacement of the stimulus positions in the direction of motion, or the lack thereof, directly determined the FLE for each trial. This method contrasts with the conventional approach of averaging offsets based on the point of subjective equality across blocks within a

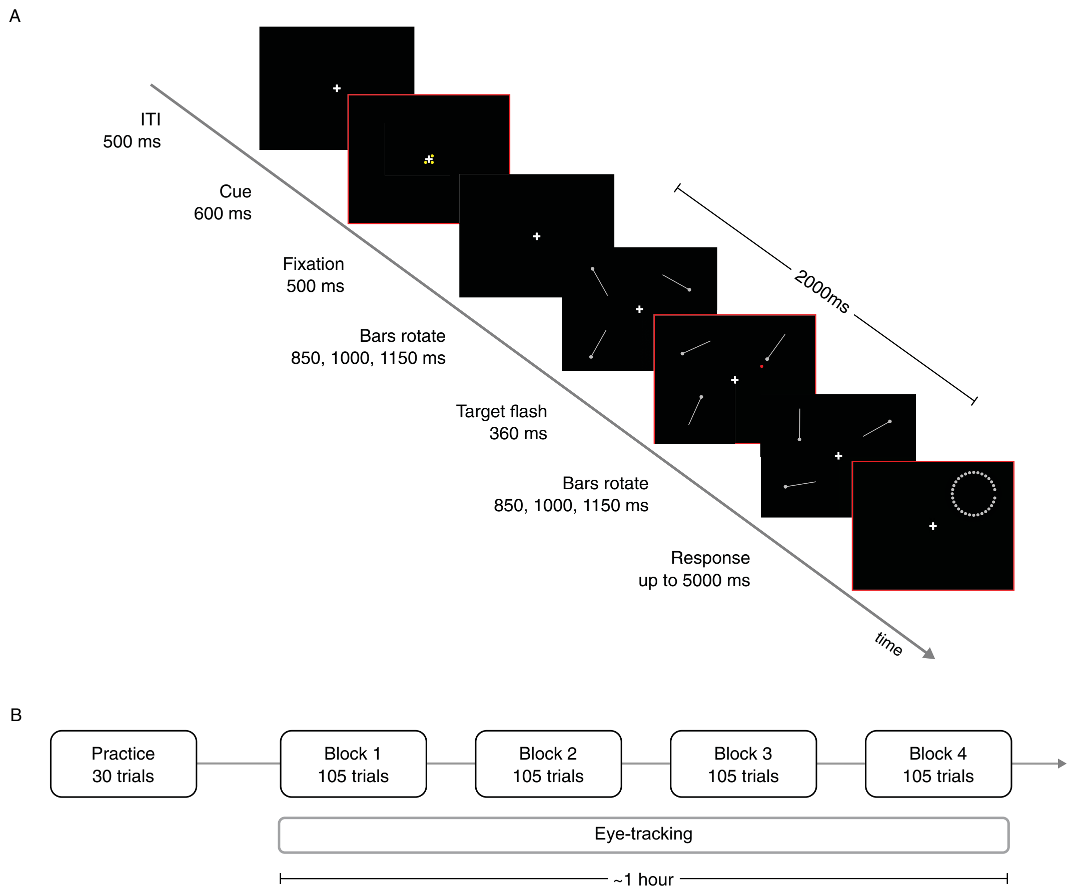

Figure 1. Experimental paradigm. (**A**) Trial sequence. Spatial attention cues were presented at the central fixation cross to indicate that the participants should orient their attention to the upcoming display, featuring an array of four rotating bars (not drawn to scale) in corresponding quadrants. The target flashed next to a bar after half the time of the overall sequence. Here, a target is presented at a cued quadrant, but sometimes the target appeared at a noncued quadrant (see text for details). Following the sequence, a response ring was presented until participants made a response. The subsequent trial began after an inter-trial interval of 500 ms. Each trial lasted up to 8 seconds. (**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 1 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.

specific condition (cf. Yook, Lee, Vossel, Weidner, & Hogendoorn, 2022).

The probe location corresponded with the quadrant where the target had been presented in the previous display, eliminating the need for participants to additionally report the target's quadrant in each trial. However, the cue–target validity varied across trials. Specifically, the target appeared in the cued quadrant(s) 90% of the time. In the remaining 10% of trials, termed catch trials, the target appeared in a noncued quadrant, and participants were instructed to press the space bar without indicating the bar's position with the response probe. Catch trials ensured participants' attention to the cues. Incorrect responses, such as responding using the probe in catch trials or pressing the space bar in noncatch trials, prompted feedback, "Please ATTEND TO THE CUES as they are helpful," at fixation for 1,000 ms. No feedback on behavioral performance was given otherwise.

The task was organized into four blocks, each consisting of 105 trials (96 noncatch trials and 9 catch trials) (Figure 1B), totaling 420 trials conducted over approximately 1 hour. Each trial lasted up to 8 seconds. Every possible combination of cue–target configurations appeared within each block with equal probability. Participants underwent four attention conditions, and the order of trials was randomized within each block. To minimize fatigue, participants were instructed to take regular self-paced breaks between blocks and between every approximately 5 and 10 mins within a given block, as indicated by a break screen.

Before the main experiment, participants completed at least 30 practice trials to familiarize themselves with the task. Upon completion of the experiment, participants were debriefed about the study's purpose related to the FLE. None of the participants reported being aware that the positions of the attended bar and target were aligned.

Data quality assessment

Data from participants who failed to identify at least 75% of catch trials were excluded from the analysis to mitigate potential noncompliance with task instructions and task artifacts. This criterion ensured participants' adherence to attending to the cued bar(s), as instructed. Data from two participants who detected an average of 2.5 ± 3.5 catch trials out of 36 throughout the experiment were excluded. Additionally, incorrectly responded noncatch trials were excluded. Among the remaining 24 participants, who on average detected 33.3 ± 2.4 catch trials, data from an average of 379 correct noncatch trials (minimum, 371; maximum, 384 ± 3.8) were available for analysis.

Behavioral analysis

Behavioral data were preprocessed using Python 3.5 (Van Rossum & Drake, 2009) within the Anaconda environment (Anaconda Inc., 2016) and analyzed in R Statistical Software v4.3.1 (R Core Team, 2023) with custom scripts.

During each trial, participants were instructed to direct their attention toward a single moving bar (focused attention condition) or spread their attention between two, three, or four bars (divided attention conditions: attend to two, three, or four). The FLE for each trial was determined by indexing the magnitude of the difference between the actual position of the target and the participant's chosen position of the bar. A value of zero indicated no perceived difference between the positions of the two stimuli. Positive values indicated a FLE, where the moving bar was perceived as ahead of the flash. Conversely, negative values indicated a flash-lead effect, where the flash was perceived as ahead of the moving bar.

Assessment of magnitude

The FLE values were aggregated to compute the median FLE magnitudes for each condition of each participant. We then compared these medians between the focused and divided attention conditions using a repeated-measures ANOVA using the four-level factor attention, with the ez package (Lawrence, 2016) in R. Following the ANOVA, we performed paired-sample *t* tests to test the hypotheses that there would be significant differences in FLE magnitudes between focused attention and divided attention conditions, as well as between the various divided attention conditions.

To account for multiple comparisons, statistically significant differences were determined based on a threshold of $p = \frac{0.05}{\mathrm{n} - \mathrm{rank} + 1}$ (one-tailed), adjusting for familywise error rate using the Holm–Bonferroni correction (Holm, 1979). Greenhouse–Geisser corrections were applied when Mauchly's test indicated a violation of sphericity.

To handle potential outliers, FLE values exceeding 3 standard deviations from the mean FLE values were identified and excluded. Analyses were performed both including and excluding outliers; however, no significant differences were observed when outliers were excluded. Therefore, the reported results include outliers, with descriptive statistics shown in Appendix A, Figure A1, to provide a more comprehensive insight into the distribution of the FLE values. To validate our findings against non-normality assumptions, we used a Friedman's test as a nonparametric alternative. The results of the Friedman's test aligned with those of the repeated-measures ANOVA.

Assessment of variability

To examine whether the distribution of FLE magnitudes became more variable with divided attention, the same procedure was repeated using the coefficient of variation (CV), calculated by dividing the standard deviation by the absolute mean of each condition of each participant. This allowed for comparing trial-to-trial variability across participants that vary widely in magnitude, by offering a relative measure of variability for comparing individuals.

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 1,000 Hz to evaluate how well participants had maintained fixation during the stimulation sequence of each trial. At the beginning of the experiment, the eye tracker was calibrated with a 5-point calibration procedure to establish an accurate gaze position of the left eye. Acceptable calibration values had to meet the validation criterion of less than 0.5 dva and maximum error of less than 1.5 dva. Owing to technical issues, eye-tracking data were not recorded for 12 participants, and 2 additional datasets were incomplete, yielding 10 analyzable datasets.

Eye-tracking data were preprocessed 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, allowing deviation of 1-dva radius from the central fixation cross. Saccades were identified using a velocity threshold of 30°/s and acceleration threshold of 8,000°/s^2. Eye-blink events were excluded.

Across attention conditions, we examined the proportion of fixation time participants spent on the central fixation cross relative to the overall time during each of three distinct phases of a trial, wherein participants were instructed to maintain fixation:

1. During the cue presentation (cue) lasting 600 ms,
2. Immediately after the cue offset (orient) lasting 500 ms, and
3. Before and after the target presentation (target), with a combined duration of 2,000 ms.

Differences in the proportion of fixation between the different attention conditions were analyzed with a repeated-measures ANOVA using the four-level factor attention.

Results

Fixation controlled under all attention conditions

The proportions of fixation time across various phases of the experiment (cue, orient, and target) are presented in Figure 2. We performed a repeated-measures ANOVA to compare the proportion of fixation between different attention conditions within each phase. There were no significant differences in fixation across cue, one-way ANOVA, attention: $F(3, 27) = 0.7$, $p = 0.5$; orient, one-way ANOVA, attention: $F(3, 27) = 0.5$, $p = 0.7$; or target phases, one-way ANOVA, attention: $F(3, 27) = 0.4$, $p = 0.8$. Overall, these results indicate that participants consistently maintained a high degree of central fixation, regardless of whether their attention was focused on a single quadrant or divided across multiple quadrants.

Attentional modulation of FLE magnitude but not trial-to-trial variability

Participants reported the perceived position of a moving bar, which was compared with its physical position. This task assessed the FLE, where the difference between the physical and perceived (reported) position of the bar at the time of the flash indicates the magnitude of the illusion. We analyzed FLE magnitudes, calculated as the average of individual medians, across different attention conditions, as shown in Figure 3A.

The illusion was prominent across all attention conditions, averaging between 15° and 20° (see Appendix A, Table A2). Overall, one-way ANOVA revealed a significant effect of attention on the FLE magnitude, $F(3, 69) = 9.2$, $p < 0.001$. Specifically,

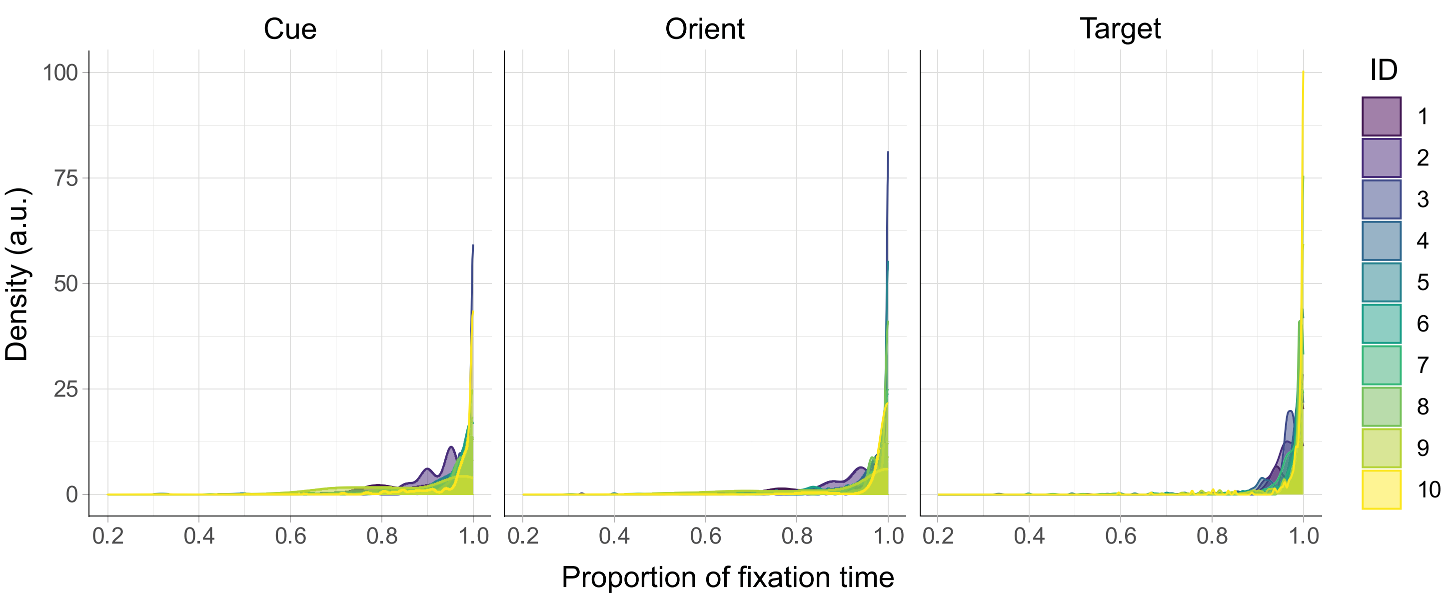

Figure 2. Individual proportions of fixation time across various phases of the experiment (cue, orient, and target), collapsed across attention conditions. Here shown are 10 participants whose eye-tracking data met the criteria for data quality. Note the fixation duration may be influenced by interruptions such as blinks, signal fallout, or saccades. These events were initially identified and removed ahead of the fixation control analysis.

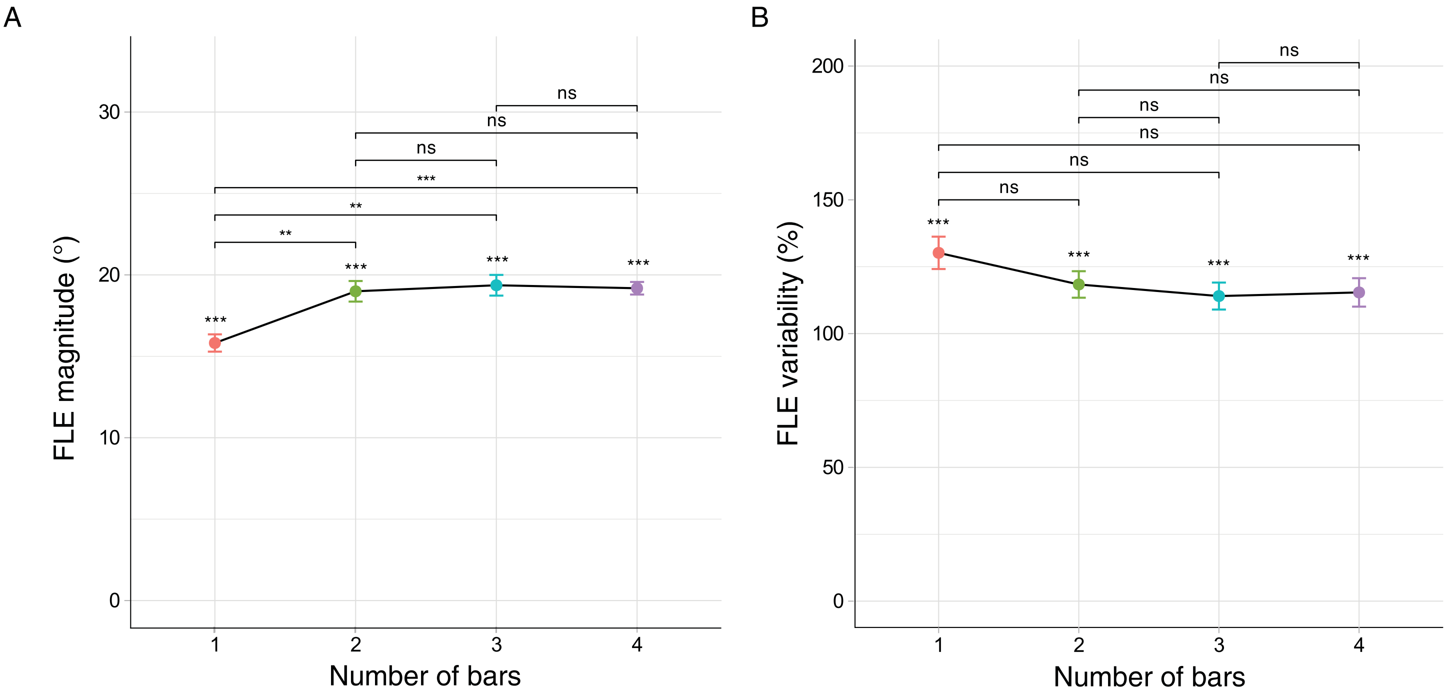

Figure 3. Flash-lag effect (FLE) results. (**A**) FLE magnitudes as a function of number of attended moving bars. All values are reported as means $\pm$ within-subject standard error of the mean (SEM, error bars). ns (not significant) denotes $p > 0.05$, ** denotes $p < 0.01$, *** denotes $p < 0.001$. (**B**) The same described in A, but for FLE variability (coefficient of variation).

	FLE magnitude	
Pair	t_{23}	*p* value
1 vs. 2	−3.9	<0.01
1 vs. 3	−4.3	<0.01
1 vs. 4	−5.2	<0.001
2 vs. 3	−0.4	1
2 vs. 4	−0.3	1
3 vs. 4	0.3	1

Table 1. Paired-sample *t* tests (one-tailed) results with correction for multiple comparisons for FLE magnitude FLE, flash-lag effect.

the mean FLE magnitudes were significantly larger in divided attention conditions (two to four bars) compared with the focused attention condition (one bar), as detailed in Table 1.

Figure 3B (see also Appendix B) depicts a contrasting pattern in trial-to-trial FLE variability, as measured as the CV, with a larger CV in focused attention than in divided attention conditions. However, no significant differences emerged across conditions, one-way ANOVA, attention: $F(3, 69) = 1.9$, $p = 0.1$. Notably, the CVs exceeding 100% indicate a high degree of variability of FLE values relative to their mean, suggesting that the FLE values varied widely within participants (see also Appendix A, Figure A1).

Discussion

In this study, we aimed to investigate how divided attention affects the perceived position of a moving object compared with a physically aligned static flash within the context of the FLE. The FLE is a well-documented illusion where a flash, when presented next to a moving object, seems to lag behind the moving object despite both being aligned physically. We found that FLE magnitude was augmented under divided attention conditions compared with focused attention. However, FLE variability across trials did not differ significantly between any of the attention conditions.

Participants viewed an array of four independently moving objects in distinct quadrants of the display during each trial. Attention was manipulated using spatial cues that directed participants to either focus on a single quadrant or to distribute attention across two, three, or four quadrants. This design allowed us to systematically compare FLE magnitude and trial-to-trial variability under different attentional loads. To ensure accurate allocation of attention, we included catch trials to verify that participants adhered to the provided cues. Subsequently, excluding catch responses from the analysis was crucial for differentiating between genuine attentional effects and potential confounding effects from incorrect cue compliance.

Our results revealed a clear effect of attention on the magnitude of the FLE. When attention was divided among multiple moving objects in different quadrants, FLE magnitudes increased significantly compared with when attention was focused on a single object. This finding aligns with previous studies (Namba & Baldo, 2004; Sarich et al., 2007; Shioiri et al., 2010) and is strengthened by our larger sample size (n = 24 compared with 15, 14, and 5, respectively) and a trial-wise measure of the FLE, which provides a more precise and nuanced understanding of the illusory effect. Interestingly, FLE variability did not show significant differences across the various attention conditions. These results suggest that although divided attention in the FLE amplifies the FLE magnitude, it does not necessarily lead to greater variability in representations from trial to trial compared with focused attention. However, it is important to note that the individual distributions of the FLE values contributed to large CVs.

Moreover, the increase in FLE magnitude was significant only when shifting from one object to multiple objects, with no further increases when attention was distributed among two, three, or four objects. This pattern is consistent with Shioiri et al.'s (2010) findings, which involved up to six dots arranged in a circle. By contrast, Hogendoorn, Carlson, Vanrullen, and Verstraten (2010) observed a gradual increase in FLE magnitude, measured as time, with a stepwise increase in FLE variability from one to two clocks, with no further increases beyond that. This suggests a saturation effect at the condition where attention was focused on two objects, indicating that further dividing attention did not significantly impact the FLE under highly divided-attention conditions (Howe & Holcombe, 2012; Luu & Howe, 2015).

Two possible explanations arise from these observations. First, as proposed by Shioiri, Yamamoto, Oshida, Matsubara, and Yaguchi (2010), the saturation effect may relate more to the spatial spread of attention than to the number of attended objects. For instance, Khurana et al. (2000) observed no changes in FLE magnitudes when one of two possible flash locations (either above or below the fixation point) was cued, similar to our study. This suggests that the effect of attention may not follow a straightforward pattern, but is highly dependent on task complexity (Khurana et al., 2000; Shioiri et al., 2010). Second, attentional resources might be constrained by hemifield (Alvarez & Cavanagh, 2005; Luck, Hillyard, Mangun, G& Gazzaniga, 1989) or even by quadrants (Carlson, Alvarez, & Cavanagh, 2007; Carlson, Cho, Turret, & Dakin, 2011). If each quadrant has a limited attentional capacity, further dividing attention might not affect the representation of additional moving objects in extra quadrants. This could account for the deviations noted in our analysis of anisotropies (see Appendix C) and the discrepancies observed in Khurana et al. (2000), where no additional attentional modulation was found compared with other FLE studies considered here. Future research could explore these mechanisms of attentional saturation by manipulating perceptual load, such as varying the number of stimuli ($>$1) within each quadrant or adjusting their eccentricities (Baldo, Kihara, Namba, & Klein, 2002). Additionally, exploring the impact of motion speed (Shioiri et al., 2010) could further provide insights into whether increased attention is needed to track faster motion (cf. Yook et al., 2022), potentially influencing FLE magnitude to a greater extent than observed here.

Our findings align with several prominent theoretical accounts of the FLE, including theories of sequential processing including temporal integration (Krekelberg & Lappe, 1999; 2000), discrete sampling perception (Schneider, 2018), attention shifting (Baldo & Klein, 1995), and postdiction (Brenner & Smeets, 2000; Eagleman & Sejnowski, 2000). For specific details of each of these theories, readers are referred to Hogendoorn (2020); Holcombe and Corbett (2023); Hubbard (2014), and Schneider (2018). Arguably, when attention is divided, the brain has fewer resources to process each object's motion trajectory, reducing information processing speed. This may contribute to increased delays in the visual system's ability to extract relevant motion and position information for each object, as the brain needs to switch between multiple objects, including the flash. This delay in processing time results in a more considerable latency difference between the moving objects and the flash, augmenting the FLE.

Under the predictive motion explanation theory (Nijhawan, 1994), these compounded delays across multiple objects may necessitate more compensation, thereby increasing the FLE magnitude. The brain might overcompensate if it prioritizes efficiency over accuracy when processing multiple moving objects under dynamic conditions, such as in this experiment. In principle, this would allow the brain to simultaneously monitor and update representations of multiple objects, even when sensory information is delayed. According to this interpretation, the attention-dependent effects of perceptual biases and illusions outlined in the Introduction can be reconciled. When attention is reduced in representational momentum and the FLE, the visual system may rely more heavily on existing predictions rather than on slowly arriving sensory input, enhancing the perceived forward displacement in moving objects. In contrast, reduced attention results in decreased extrapolation during multiple object tracking. This occurs because the task requires continuous and precise tracking of several objects, and the brain cannot allocate enough resources to accurately predict each object's motion trajectory, leading to less effective extrapolation. Hence, the impact of reduced or divided attention varies depending on the nature of the task. Although our findings are open to interpretation, we believe our findings contribute to this body of evidence by revealing the role of attention in efficiently processing multiple moving objects in dynamic environments. By contrast, our findings do not seem to align with the differential processing latencies theory (Whitney & Murakami, 1998; Whitney, Murakami, & Cavanagh, 2000), which would predict that, as moving objects are processed faster than static objects, divided attention would lead to a smaller processing latency difference between the two and a smaller FLE magnitude.

Taken together, these results suggest that, in the context of the FLE, attention primarily influences the rate at which events are processed within the visual system, rather than the quality of processing. Although overall perception is certainly impacted by the quality of representation, the FLE seems to be more a result of how the visual system effectively manages highly attention-demanding and dynamic environments. This suggests that when attentional resources are divided among multiple moving objects, delays in accessing relevant information may accumulate (Carrasco & McElree, 2001; Giordano, McElree, & Carrasco, 2009), leading to slower recognition of motion and delayed availability of position information for each object.

An alternative interpretation is that attention affects the anticipatory processing of the flash (Baldo et al., 2002; Vreven & Verghese, 2005), potentially decreasing the latency difference between the flash and the moving object when attention is focused. Although it is challenging to rule out an effect of divided attention on the flash, this alone is unlikely to account for our results. This interpretation would also predict increased FLE magnitudes with divided attention, but it assumes that participants might anticipate the flash even without explicit cues. Previous studies (Baldo et al., 2002; Sarich et al., 2007; Shioiri et al., 2010; Vreven & Verghese, 2005) may have been confounded by this. However, our study's use of catch trials decreases reduces the likelihood that participants were simply waiting for the flash. If participants had been passively anticipating the flash, then they would have reported the FLE regardless of the attentional cues. Our data show that participants did notice the flash when it appeared next to a noncued bar, suggesting that they did not merely wait for the flash on every trial. Although our analyses concentrated on correctly responded noncatch trials, future research could include a separate condition for catch trials. A lack of discernable difference in FLE magnitudes between catch and noncatch conditions would strongly suggest that the changes observed were primarily driven by the flash itself. This would offer further insights into how attention affects the representation of moving objects rather than the detection of the flash.

In conclusion, the experiment reported here is the first to manipulate attention in the flash-lag paradigm combining conventional attentional cueing with divided attention procedures, alongside trial-wise FLE readouts. Our results demonstrate that the magnitude of motion-induced illusory perceptual effects varies with the level of attention in dynamic environments.

Keywords: flash-lag effect, visual attention, divided attention, multiple moving objects, spatial cues

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Appendix A: Descriptive statistics of FLE magnitude

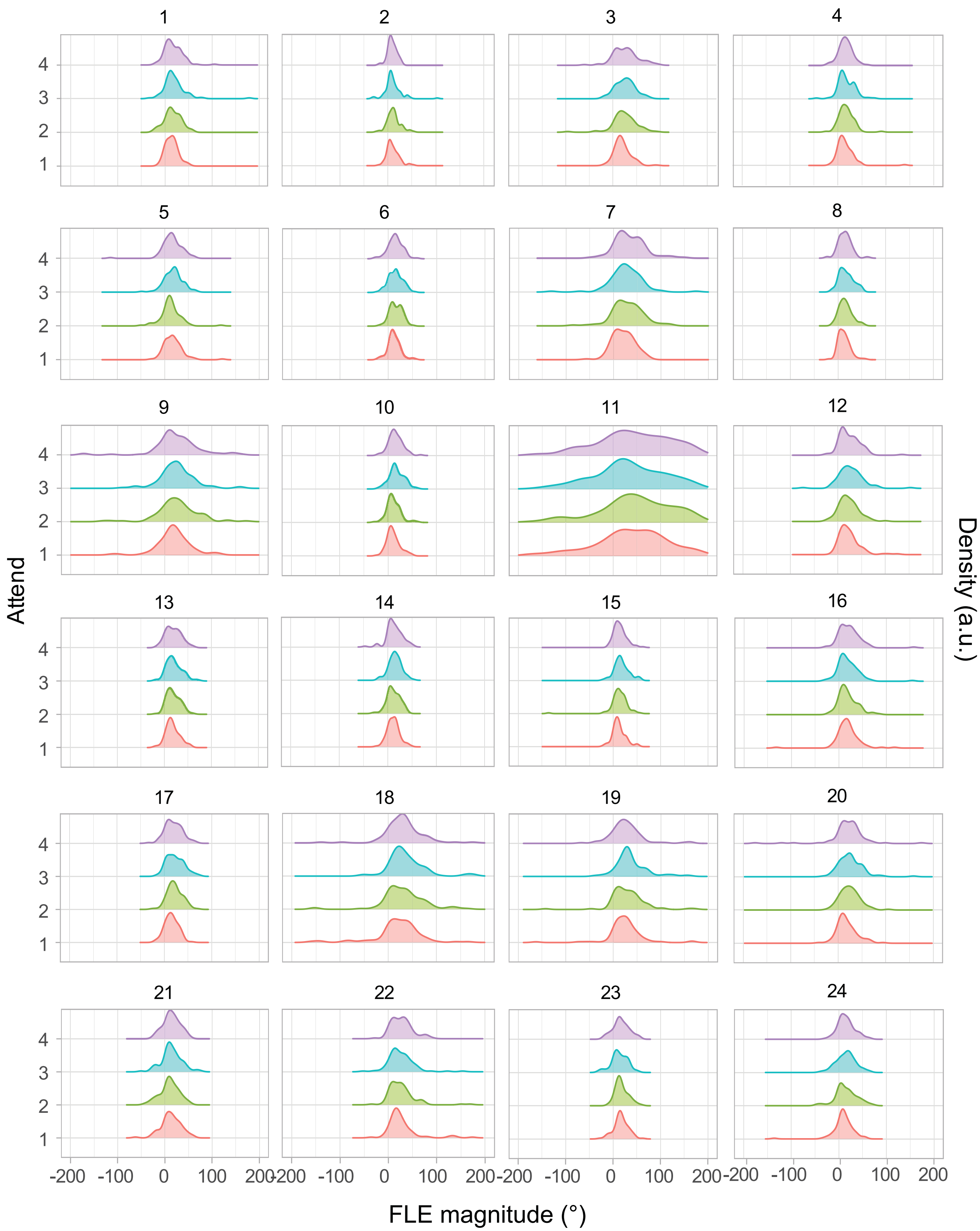

Figure A1. Individual distributions of FLE magnitudes across attention conditions.

Bars	*M*	*SD*	t_{23}	*p*
1	15.8°	6.4°	12.1	<0.001
2	19.0°	9.0°	10.3	<0.001
3	19.4°	6.5°	14.6	<0.001
4	19.2°	7.2°	13.0	<0.001

Table A2. One-sample *t*-test (one-tailed) results against zero.

Appendix B: Descriptive statistics of FLE variability

Bars	*M*	*SD*	t_{23}	*p*
1	130.2%	45.3%	14.1	<0.001
2	118.4%	36.2%	16.0	<0.001
3	114.0%	32.2%	17.3	<0.001
4	115.4%	32.2%	17.6	<0.001

Table B1. One-sample *t*-test (one-tailed) results against zero.

Appendix C: Hemifield effects in the FLE

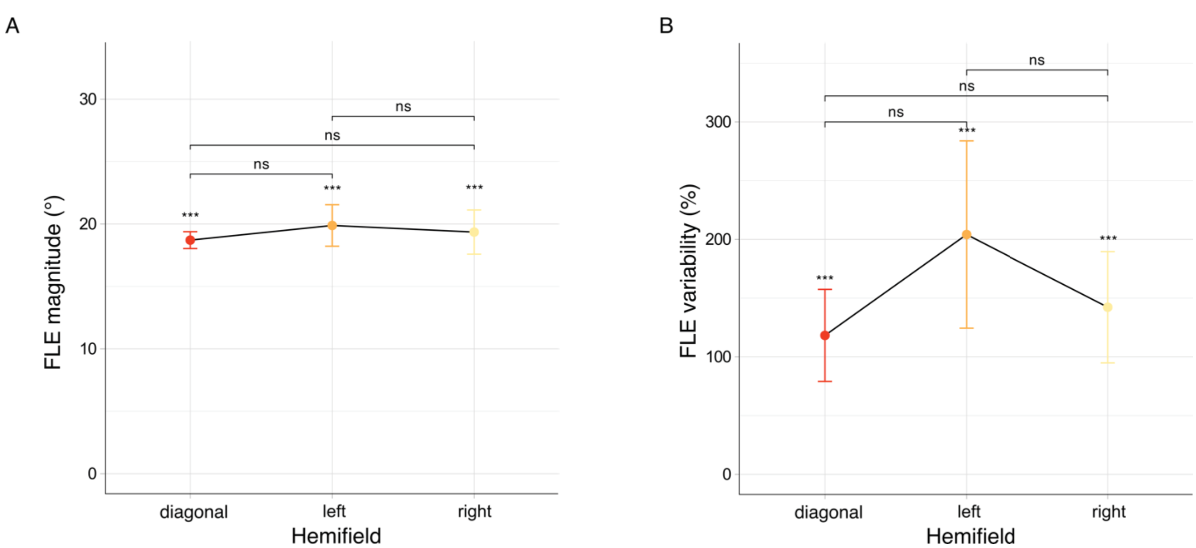

Figure C1. Hemifield results. Previous studies using linear motion have demonstrated anisotropies in the left and right sides of the visual field (Kanai, Sheth, & Shimojo, 2004; Shi & Nijhawan, 2008; Suzuki, Atmaca, & Laeng, 2023). Notably, the FLE tends to be more substantial when stimuli are presented in the left hemifield. Here, we aimed to test whether the effect of divided attention could be pronounced with these anisotropies, particularly within the attend-to-two condition. To achieve this, we examined the magnitude and variability of the FLE on trials where participants were cued to two quadrants within their left, right, or diagonally across the upper and lower visual hemifields. (**A**) The FLE magnitudes are plotted as a function of the to-be-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 both the right or diagonal hemifields, no significant modulation of attention was detected (one-way ANOVA, *hemiField:* $F(2, 46) = 0.2$, $p = 0.7$). (**B**) The same as described in **A** but for FLE variability (one-way ANOVA, *hemiField:* $F(2, 46) = 0.6$, $p = 0.5$).