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Contributions of visible persistence and perceptual set to the flash-lag effect: Focusing on flash onset abolishes the illusion

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ABSTRACT

Among other theories, visible persistence has been suggested to explain the flash-lag effect (FLE). According to this account, the flash is not compared to the moving object at its perceived onset, but at a later time while it is still subjectively visible. Therefore, it is reported to lag the moving object. We show that observers' perceptual set determines whether the persisting image of the flash or its onset is used to judge relative position. Spontaneously, observers use the persisting image, such that a flash-lag results. When forced to focus on the onset of the flash because flashes and stationary onset-only stimuli are mixed, observers base their judgments on the onset and the FLE is abolished. We found that perceptual set affected the FLE in the flash-initiated and in the continuous-motion paradigm. Finally, we showed that the position of the moving object was perceived without any blur and that the flash persisted subjectively for at least 60–80 ms. Changes of perceptual set and visible persistence may underlie many of the previously reported modulations of the FLE.

1. Introduction

In the flash-lag effect (FLE), a flash is perceived to lag a moving object when their positions are physically aligned (MacKay, 1958; Metzger, 1932; Nijhawan, 1994). Nijhawan (1994) explained this illusion by a mechanism of motion extrapolation which provides advance perception of the moving object's position to overcome neural delays. Since Nijhawan's report, a large number of explanations have been put forth that have been extensively reviewed elsewhere (Krekelberg & Lappe, 2001; Nijhawan, 2002, 2008; Whitney, 2002). A brief overview of the different approaches may nonetheless be in order. The differential latency account claims that the latency of the flash is longer than the latency of the moving object, so that the flash seems to lag the moving object (Patel, Ögmen, Bedell, & Sampath, 2000; Purushothaman, Patel, Bedell, & Ögmen, 1998; Whitney & Murakami, 1998). Possibly, the latency of the moving object is variable at motion onset and only reaches a constant value after some time (Ögmen, Patel, Bedell, & Camuz, 2004). The primary finding supporting differential latencies is the effect of luminance: Bright, short-latency flashes reduce or reverse the FLE (Patel et al., 2000; Purushothaman et al., 1998). By contrast, sampling accounts are based on the assumption that the perceived position of a moving object is the result of spatio-temporal integration. When the flash is presented, the samples preceding the flash are devalued and new samples have to be gathered to estimate the moving object's position. Thereby, the integration window is not centred on the perceived flash and mislocalization in the direction of motion occurs (Brenner & Smeets, 2000; Eagleman & Sejnowski, 2000a). The primary evidence for this view is that changes occurring after the flash change the size of the FLE (e.g., a change in speed, Brenner & Smeets, 2000). While the aforementioned accounts refer to low-level motion processing, Baldo and Klein (1995) suggested the involvement of attentional mechanisms. Attention is necessary for visual events to reach consciousness and some time is necessary for attention to move from the moving object to the flashed object. Thus, the time to shift attention results in delayed perception of the flash. The most convincing evidence for the attentional account is that voluntarily attention to the moving object reduces the flash-lag effect (Namba & Baldo, 2004), but effects of attention on the FLE have not always been confirmed (Khurana, Watanabe, & Nijhawan, 2000).

1.1. Visible persistence and the FLE

In the present paper, we will test an account of the FLE in terms of visible persistence. Walker and Irion (1982) were the first to explain the perceptual lag of a flash by visible persistence (see Fig. 1A). According to the authors, visible persistence of the flash exceeds persistence of the moving object and "during the period of visible persistence, the image of the flash remains essentially

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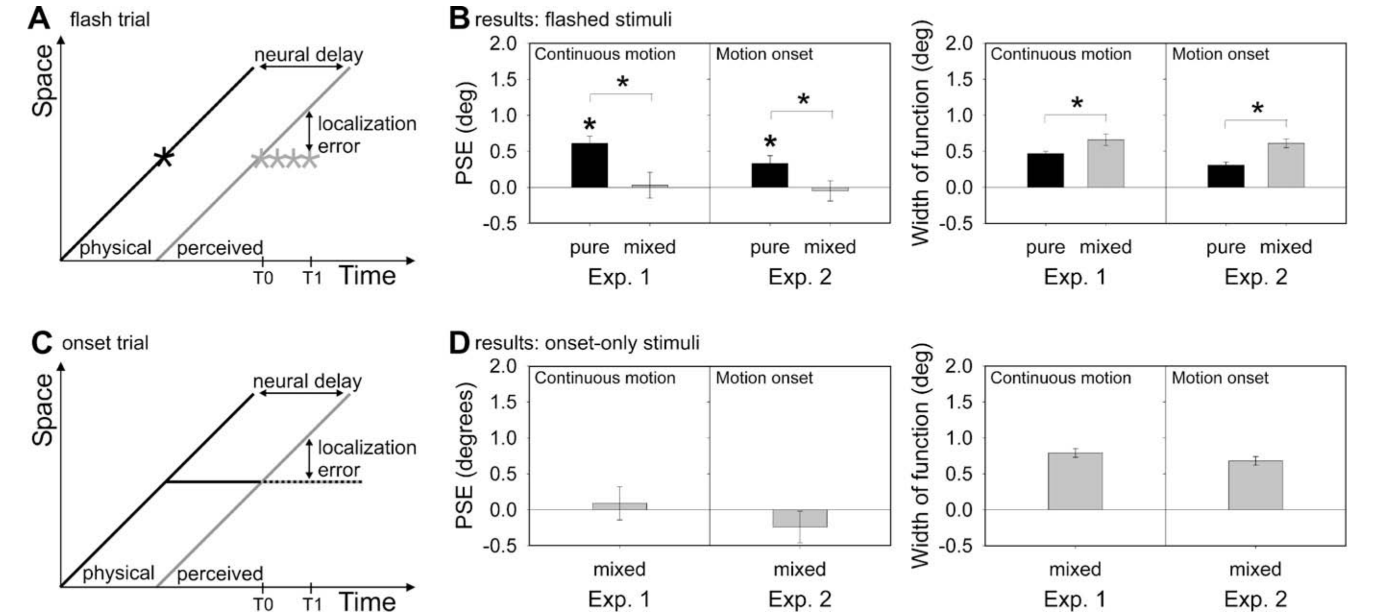

Fig. 1. Illustration of experimental hypothesis and results. *Panel A* illustrates "flash" trials. The flash was physically displayed for one frame at the same position as the moving object. The flash and the moving object are perceived after a neural delay. We believe that the neural delay is equal for moving and stationary objects, but our hypothesis does not depend on this assumption. The flash's image persists for some time while the moving bar is seen without blur. A decision about the relative position of the objects may be reached at the perceived onset of the flash ($T0$) or at some later point, for instance, the perceived offset ($T1$). A decision at $T0$ results in accurate reports, whereas a decision at $T1$ results in a localization error (indicated by the vertical arrow). *Panel C* illustrates "onset" trials. A stationary bar was displayed instead of a flash. As with flash trials, a perceptual decision may be made at the perceived onset ($T0$) or later ($T1$). *Panels B and D* show the results of Experiments 1 and 2. Mean points of subjective equality (PSE) and the width of the psychometric functions (i.e., the parameter a) are graphed as a function of experimental condition. Wide functions (i.e., flat curves) indicate poor discrimination. In the "pure" condition, only the flash trials were displayed whereas in the "mixed" condition, both "onset" and "flash" trials were run. The flash was presented during ongoing motion in Experiment 1 and at motion onset in Experiment 2. *Panel B* shows the data from flash trials. *Panel D* shows the data from the onset trials. Error bars denote the between-subjects standard error. Asterisk (∗) = significant t-test.

fixed in space on the retina while the continuously lighted portions of the image move on, leaving the flash apparently lagging behind." (p. 215). In support of their account, they showed that the FLE decreased when the background luminance increased. It is known that the persistence of a flash is inversely related to the background luminance (Allport, 1970). That is, the higher the background luminance, the shorter did the flash persist and the smaller was the FLE.

1.2. Previous evidence against the visible persistence account

Previous studies have quickly rejected explanations in terms of visible persistence in favour of more elaborate theories. Whitney, Murakami, and Cavanagh (2000) questioned the visible persistence account by demonstrating that the FLE did not change when the offset of the flash was removed. In their Experiment 1, two moving segments and a flashed dot were displayed. A mask of the same height, luminance as the flash, but extending horizontally across the entire area of the screen, was presented one video frame (15 ms) after the flash. Whitney et al.'s results showed that the mask did not change the FLE, suggesting that visible persistence (which was presumably absent with the mask) does not explain the FLE. However, Whitney et al. never measured visible persistence of their stimuli and we do not know to what extent persistence was reduced. In general, it has been demonstrated that a mask reduces visible persistence but does not abolish it (Castet, 1994; Coltheart, 1980). Further, masking the stimulus has several perceptual consequences that make the results difficult to interpret. First, eliminating the offset of the stimulus seriously degrades its visibility. Poor visibility increases uncertainty about the flash location and uncertainty is known to increase the FLE (Baldo, Kihara, Namba, & Klein, 2002; Brenner & Smeets, 2000; Eagleman & Sejnowski, 2000b; Vreven & Verghese, 2005). Second, it may be that masking changes the latency of the flash. Possibly, poorly visible stimuli have a longer latency, in analogy to the prolongation of latencies by low luminance (Patel et al., 2000; Purushothaman et al., 1998). In sum, studies of masking do not provide unambiguous evidence against an account in terms of visible persistence because masking may change more than one aspect of stimulus processing (in unknown ways). Also, as we will show, the perceptual decision may occur sometime during visible persistence and not necessarily at perceived flash offset. Therefore, trimming visible persistence by masking only affects perceptual judgments if the remaining visible persistence is shorter than decision time.

Another argument against the visible persistence account was provided by Baldo et al. (2002). They demonstrated that the FLE was unchanged when the moving object was compared to the onset or offset of a stationary stimulus. Importantly, they tested flash, onset, and offset trials in separate blocks of trials. In the onset condition, the only unique event is the appearance of the stimulus and visible persistence does not occur because the stationary stimulus stays on the screen. Nonetheless, there may be a constant lag before a perceptual decision is reached (see Fig. 1C) in order to increase certainty about the decision. Developing such a perceptual set is only possible if onset-only stimuli are shown in a separate block of trials. Otherwise, observers would miss relevant information in flash trials (see below).

2. Experiments 1 and 2

In the following experiments, we tested an account of the FLE that combines low-level visible persistence and high-level perceptual set. Because perception of the flash is not an instantaneous process (for a review see Breitmeyer & Ögmen, 2006; Coltheart, 1980), the comparison between the moving object and the flash may occur at different times. It may occur at the perceived onset of the flash, while it is subjectively present, or at its perceived offset. If the comparison does not occur at perceived flash onset, the moving object has already moved to the next perceived position and a lag is reported. We think that this is what happens in typical FLE paradigms. Note that we suppose that the initial perception of flash and moving object is accurate (equal latency, no extrapolation, etc.). In contrast, all other theories would claim that there is a spatial or temporal error in the perception of flashed and moving objects. Rather, we argue that the FLE arises from a decisional lag that depends on the perceptual set of the observers. By perceptual set we refer to a bias or readiness to perceive certain aspects of available sensory input while ignoring others.

When observers are certain that a flash will be presented on a given trial, they do not report the relative position of the moving object at perceived flash onset, but at some later time while the flash is still visible (time *T*1 in Fig. 1A). This perceptual set results in the FLE. However, characteristics of the trial context may advance the perceptual decision to the perceived onset of the flash (time *T*0 in Fig. 1A). To change perceptual set, we presented observers with both onset-only and flash stimuli in random order. In trials with onset-only stimuli, there is only a single unique event, the onset of the stationary stimulus. In contrast, the subjective experience of the flash is an extended event due to visible persistence. Therefore, perception of the flash has a perceived on- and offset. Observers will rapidly notice that the only singular perceptual event that occurs in both trial types is the perceived stimulus onset. Therefore, observers will focus on the perceived stimulus onset. This perceptual set is expected to abolish the lag. In other words, perceptual decisions are no longer taken at some moment between the perceived on- and offset of the flash because observers cannot be certain that there will be an offset. Similarly, observers no longer report the relative position of onset-only stimuli with a constant delay because they cannot be sure that the stimulus will stay on the screen.

In Experiments 1 and 2, we evaluated the FLE in "pure" and "mixed" conditions, which differed in the type of trials that were shown. In the "pure" condition, the position of a flash had to be compared to the position of a moving object (standard FLE condition). In the "mixed" condition, the position of a moving object had to be compared to the onset of a stationary bar in one half of the trials and to a flash in the other half of the trials, randomly interleaved. In Experiment 1, the perceptual judgments had to be made during ongoing motion, whereas in Experiment 2, the judgement had to be made at motion onset. In Experiment 3, we investigated whether there was motion blur by estimating the perceived width of a moving object. In Experiment 4, our aim was to define the perceived duration (or visible persistence) of the flash by matching it to a longer "flash" with a lower contrast.

2.1. Method

2.1.1. Participants

Students at the University of Geneva participated in these experiments. They reported normal or corrected to normal visual acuity. Participants took part only in a single experiment. Thirty-four students participated in Experiment 1 and 39 in Experiment 2.

2.1.2. Apparatus and stimuli

Stimuli were generated by a ViSaGe graphics adaptor (Cambridge Research System, Rochester, UK) and presented on a 21 in. monitor (Mitsubishi Diamond Pro 2070SB) at a resolution of 1024×768 pixels at 100 Hz. The background was gray, CIE (1930) chromatic coordinates of ($x = 0.279$, $y = 0.303$), with a luminance of 65.52 cd/m^2. Stimuli were black rectangular bars ($0.3^\circ \times 4.24^\circ$, horizontal $\times$ vertical). A $0.9^\circ \times 0.9^\circ$ fixation cross was displayed at the centre of the screen. Eye fixation was monitored by a High Speed Video Eyetracker (Cambridge Research System, Rochester, UK). About 10% of the trials were discarded due to fixation errors in Experiment 1 and ~6% in Experiment 2.

Two black bars were displayed below the central fixation point. The upper of the two bars was the target and the lower was the probe stimulus (see Fig. 2A). The target was at an eccentricity of 3.34° to the nearest edge and it moved horizontally at a velocity of 16.79°/s. The distance between target and probe was 0.03°. Two types of trials were run, "flash" and "onset" trials. In flash trials, the bar appeared for one frame which corresponds to 10 ms. In onset trials, a stationary bar appeared instead of a flash and remained visible until the end of target motion. In the "mixed" condition, flash and onset trials were randomly intermixed. In the "pure" condition, only the flash trials were run. The probe (flash or stationary bar) was presented at different trajectory positions. In Experiment 1, the probe was presented during ongoing target motion. In Experiment 2, the probe was displayed at the onset of target motion. In both experiments, the relative position of the probe was randomly varied. Negative probe positions indicated that the probe appeared behind the moving target. Nine relative positions between moving target and probe bar were selected. The positions of the probe were distributed from −2.52° to 4.2° in steps of 0.84°. The horizontal target position at probe onset was jittered by ±2.52 around the screen centre. The direction of target motion was random and the nine relative positions were paired with two directions of motion. The average duration of target motion was 1 s in Experiment 1 and 0.5 s in Experiment 2.

2.1.3. Procedure

The experiments took place in a dimly lit room. Participants viewed the stimuli at a distance of 52 cm from the monitor and head movements were restricted by a chin and forehead rest. In each experiment, they were instructed to fixate the central fixation cross. Participants were randomly assigned to one of two groups, the "pure" and the "mixed" condition. Their task was to press one of two keys to indicate whether they perceived the lower bar (flashed or stationary) as appearing to the right or to the left of the moving target. The participants in the "mixed" condition worked through 1152 trials in two sessions. In each session they performed 576 trials (2 probe conditions $\times$ 9 spatial offsets $\times$ 2 directions $\times$ 16 repetitions). Subjects in the "pure" condition performed 576 trials in two sessions of 288 trials (9 spatial offsets $\times$ 2 directions $\times$ 16 repetitions). The first session was considered as training for both groups and the data were discarded.

2.2. Results and discussion

We converted the left/right responses into ahead/behind judgments. Then, we fit the logistic function: $y = 1/(1 + \exp(-(x - c)/a))$, where a indicates the width of the curve, c estimates the point of subjective equality (PSE) between probe and target position, x indicates the relative position between the flash and the moving target, and y the relative frequency of "ahead" responses. Negative PSE values indicate that the position of the probe had to be displayed behind the moving target in order to perceive the two bars as aligned. Conversely, positive values indicate that the position of the probe had to be displayed in front of the moving target. Further, we considered the width of the psychometric function, a. The width provides a measure of observers' ability to discriminate stimuli. When the just noticeable difference is large, the psychometric function will be wide. Further, the width parameter a allows to calculate the slope of the sigmoid curve at its steepest point, with slope = $1/(4a)$.

Psychometric functions were calculated for each condition and participant. The fit of individual functions was good (R-square close to 1.00). To evaluate differences between conditions and differences from zero, t-tests were conducted on PSEs and the width of the psychometric functions. Data from the two experiments are depicted in Fig. 1 (*Panels B* and *D*).

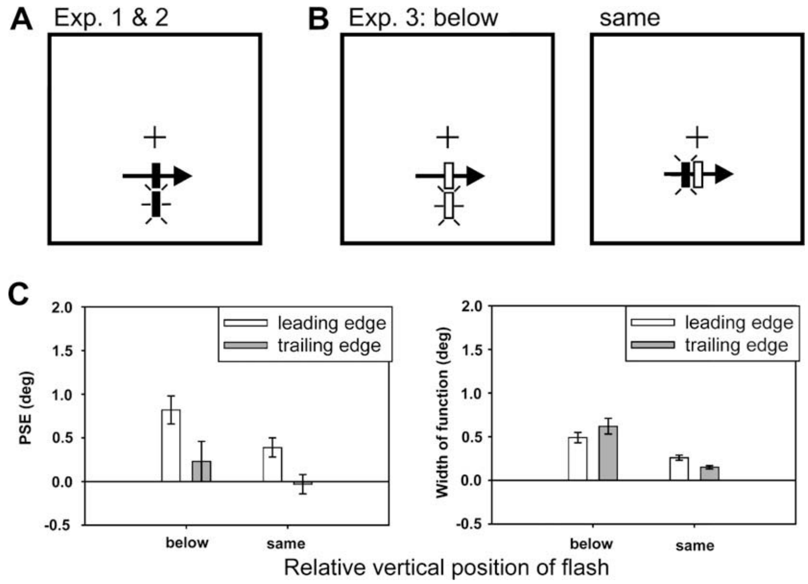

Fig. 2. Illustration of experimental conditions and results of Experiment 3. *Panel A* illustrates the position of the moving and flashed object in Experiments 1 and 2. *Panel B* illustrates the relative position of the flash in Experiment 3. The flash was either displayed below the moving object or at the same vertical position as the moving object. *Panel C* shows mean points of subjective equality (PSE), width of the psychometric functions (i.e., the parameter *a*), and between-subject standard error as a function of experimental condition and task. The "behind"-task estimates the perceived trailing edge of the moving bar. The "ahead" task estimates the perceived leading edge of the moving object.

2.2.1. Experiment 1

We observed a significant FLE in the "pure" condition (0.61° or 36 ms), $t(16) = 6.32$, $p < .001$, but not when flash trials were mixed with the onset trials (0.03° or 1 ms), $t(16) = 0.15$, $p = .87$. The difference of 0.58° was significant, $t(32) = 2.8$, $p = .009$, suggesting that the illusion was eliminated by focusing participants' attention on the onset of the flash. Nevertheless, discrimination of the flash position was better (i.e., the psychometric functions were not as wide) in the "pure" condition than in the "mixed" condition (0.31 vs. 0.61), $t(32) = 4.46$, $p < .001$. We believe that the heterogeneous nature of the trials and the need to pay attention to the onset, which does not correspond to participants' natural strategy, made it more difficult for participants to make precise judgments. As a result, psychometric functions were somewhat wider.

Further, with onset-only stimuli in the mixed condition (see Fig. 1D), we did not find a lag during ongoing motion (0.09° or 5 ms), $t(16) = 0.38$, $p = .71$. This is in apparent contradiction with a study by Baldo et al. (2002). They found a lag of the same magnitude in both onset-only and flash conditions; in particular the perceptual error was estimated to range between 40 ms and 60 ms for short eccentricities.[1] Contrary to our paradigm, the onset and flash trials in Baldo et al. were run in separate blocks. Thus, the perceptual set may have been different in the two types of trials. As outlined above, perceptual decisions may be based on a later moment in order to be more certain about the relative location of onset-only stimuli. In fact, the results for flash trials showed that perceptual set strongly influences the perceptual error.

2.2.2. Experiment 2

When the flash was displayed at motion onset (see Fig. 1B) we found a significant FLE in the "pure" condition (0.33° or 20 ms), $t(19) = 2.99$, $p < .05$. The FLE at motion onset was not larger than the FLE during ongoing motion in the "pure" condition of Experiment 1. Actually, it tended to be smaller (difference of 0.28°), $t(35) = 1.85$, $p = .073$. Studies that reported no difference between the FLE at motion onset and the FLE during ongoing motion presented the flash at a small distance from the moving object (Eagleman & Sejnowski, 2000a; Khurana & Nijhawan, 1995) as was the case in the present study (distance smaller than 1°). Studies reporting a larger FLE at motion onset than during ongoing motion presented the flash at a large distance from the moving object (Baldo & Klein, 1995; larger than 6° in Gauch & Kerzel, 2008; for conflicting results see Linares, Lopez-Moliner, & Johnston, 2007). Similar to the results of Experiment 1, the FLE effect was eliminated when flash and onset trials were mixed (−0.05° or 3 ms), $t(18) = -0.34$, $p = 0.74$. The difference between the FLE in the "pure" and "mixed" conditions was significant (difference of 0.28°), $t(37) = 2.15$, $p = .04$.

With onset-only stimuli displayed at motion onset, we found no significant lag effect (−0.24° or 14 ms), $t(18) = -1.1$, $p = 0.29$ (see Fig. 1D), suggesting that there was no Fröhlich effect (Fröhlich, 1923) in our paradigm. The Fröhlich effect is the displacement of the perceived onset of a moving object in the direction of motion relative to a fixed spatial reference (Fröhlich, 1923; Müsseler & Aschersleben, 1998). The most likely reason for the absence of a Fröhlich effect is the relatively slow target motion (Gauch & Kerzel, 2008; Kerzel, in press; Kreegipuu & Allik, 2004). Similar to Experiment 1, discrimination was better when the flash was displayed in a "pure" block than when it was mixed with onset-only stimuli (difference of 0.19°), $t(37) = 2.35$, $p = .03$.

In sum, the results of Experiments 1 and 2 consistently showed that the FLE was eliminated when flash and onset-only stimuli were presented in the same block of trials.[2] We suggested above that the inter-trial context changed participants' perceptual set

[1] We successfully replicated Baldo et al.'s (2002) study by presenting onset-only stimuli during continuous motion in a separate block of trials. We found a significant lag of 1.03° or 62 ms, $t(7) = 3.83$, $p < .01$, which is in the range of their results.

[2] A reader of the manuscript wondered whether we would obtain similar results if the same group of observers worked though pure and mixed blocks (within-subject design). We ran six observers in a continuous-motion paradigm and obtained results similar to our between-subjects design: The lag with flashes was larger in pure than in mixed blocks (0.59° vs. 0.09°), $t(5) = 4.06$, $p = .01$. *t*-tests against zero showed that the flash-lag effect was significant in pure (0.59° or 35 ms), $t(5) = 2.97$, $p = .03$, but not in mixed blocks (0.09° or 6 ms), $p > .59$. There was also no lag of onset-only stimuli in mixed blocks (−0.17° or 10 ms), $p > .58$.

so that they made perceptual judgments at the onset of the flash. Thus, it is possible to discourage participants from judging relative position based on the persisting image of the flash. Note that we did not explicitly ask observers to do so, but the task demand was implicit in the set of trials that was presented to them. It would be interesting to see whether instructions to focus on flash onset while ignoring the persisting image had the same effect. However, we were afraid that naïve observers may have difficulty in dissecting the subjective experience of the flash. Instead, instructions to attend to the onset may induce undesirable strategies to compensate for localization errors.

3. Experiment 3

In Experiment 3, our aim was to test whether the moving object was accurately perceived without any smear. This would lend support to the hypothesis that the FLE is due to the comparison between a subjectively persisting flash and a subjectively sharp, deblurred object in motion. Burr (1980) proposed that motion detectors suppress the smear produced by the successive positions of moving objects. While there was motion smear for short stimulus durations that resulted in a weak sensation of motion, there was very little smear at longer durations when the sensation of motion was stronger. Nevertheless, it has been demonstrated that a single moving dot looks smeared and that the magnitude of the smear decreases when the density of the dots is increased, suggesting the involvement of masking or inhibition from nearby objects (Chen, Bedell, & Ögmen, 1995).

In previous studies (e.g., Burr, 1980; Chen et al., 1995), motion smear was measured by asking observers to match the length of a comparison line to the perceived motion streak. Here, we opted for a method that was more strongly related to the localization tasks used in Experiments 1–2. For one group of participants, the task was to judge whether there was something behind the flash, which estimated the perceived trailing edge of the moving bar. For the other group, the task was to judge whether there was anything ahead of the flash, which estimates the perceived leading edge of the moving bar. The difference between the perceived leading and trailing edge gave us the perceived width of the bar. Further, we varied the position of the flash. In the "same" condition, we displayed a red flash that appeared on the trajectory of a moving bar. In the "below" condition, the flash appeared next to the trajectory of the moving object (as in the previous experiments, see Fig. 2B).

3.1. Method

3.1.1. Participants

Seventeen students at the University of Geneva participated in this experiment. Eight subjects were randomly assigned to the "ahead" task and nine to the "behind" task. They reported normal or corrected to normal visual acuity.

3.1.2. Apparatus and stimuli

Apparatus and stimuli were as in Experiment 1 with the following exceptions. Depending on the conditions, white ($x = 0.279$, $y = 0.303$, $z = 131.04$) or red flashes ($x = 0.613$, $y = 0.338$, $z = 20.636$) were displayed. To allow for comparison with previous studies (e.g., Burr, 1980; Chen et al., 1995), we used a moving object that was brighter than the background. A white bar moved horizontally with a velocity of 16.79°/s at an eccentricity (edge-to-edge) of 3.34° below the fixation cross. In one condition, a white bar was flashed 0.3° below the moving object. In another condition, a red bar was flashed at the same vertical position as the moving object (see Fig. 2B). In the "ahead" task, the horizontal flash position with respect to the moving object varied between −1.26° and 2° in steps of 0.42°. In the "behind" task, the horizontal flash position was between −1.43° and 1.43° in steps of 0.34°. As in Experiments 1 and 2, the horizontal target position at probe onset was jittered by ±2.52 around the screen centre and the direction of target motion was random.

3.1.3. Procedure

The two vertical flash positions (same, below) were run within-subject, while the type of question was run between-subjects. In one group, the task was to judge whether the moving target was ahead of the flash. In another group, the task was to judge whether the moving target was behind the flash. Vertical flash position was blocked in each session and block order was counterbalanced across subjects. About 4% of the data were discarded due to fixation errors.

Each group worked through 1152 trials in two sessions. In each session they performed 576 trials (2 vertical flash positions × 9 spatial offsets × 2 directions × 16 repetitions) and the first session was considered as training for both groups and the data were discarded.

3.2. Results and discussion

PSEs and width of the psychometric functions are depicted in Fig. 2C. We conducted a two vertical flash positions (same, below) × two tasks (ahead, behind) mixed-factors ANOVA on PSEs. There was a significant effect of task, $F(1, 15) = 7.11$, $p = .018$, indicating that PSEs for the trailing edge (0.1° or 6 ms) were smaller than PSEs for the leading edge (0.61° or 36 ms). The main effect of vertical flash position reached significance, $F(1, 15) = 7.77$, $p = .014$, indicating that PSEs were larger when the flash was presented below (0.55° or 33 ms) than when it was presented at the same vertical position (0.2° or 11 ms). This result is consistent with a previous study showing that the FLE increased with increasing separation between the moving object and the flash (Baldo & Klein, 1995).

Discrimination was better when the flash was presented at the same vertical position than below (0.23 vs. 0.56), $F(1, 15) = 4.64$, $p = .05$. Further, analysis of the width of the psychometric functions revealed a significant interaction, $F(1, 15) = 39.81$, $p < .001$, between eccentricity and task (see Fig. 2C, right graph).

Next, we subtracted the PSE of ahead from the PSE of behind judgments. The difference between the PSE values of the two tasks provides an estimate of the perceived length or smear of the moving object. We obtained a value of 0.27° which is close to the veridical width of the bar (0.21°). This result is inconsistent with studies that showed motion smear for isolated targets (Chen et al., 1995). However, a number of methodological differences may account for the discrepancy. Chen et al. used presentation times shorter than 150 ms while our motion stimulus was visible for 500 ms on average before the flash was presented. They measured the length of the motion streak with an adjustment procedure, while we used localization judgments. Finally, they presented their stimuli on a much brighter background (200 cd/m^2 vs. 65.52 cd/m^2 in our study). We do not know which factor explains the discrepancy, and future research should investigate motion smear in the various conditions. Here, the important point to note is that the moving object was perceived without any blur in our paradigm.

4. Experiment 4

While the perceived outline of the moving object was sharp, we speculated that perception of the flash was extended in time. To measure visible persistence, we used simultaneity judgments combined with adjustments of stimulus contrast. According to Bloch's law (1885), it is possible to trade off stimulus contrast and duration to maintain a constant perceptual experience: $R = I \times T$, where R stands for response, I for intensity and T for time. Hence, the subjective duration of a brief flash with high contrast can be matched to a longer stimulus with lower contrast (see Fig. 3A). We asked observers to adjust the contrast of a test stimulus of fixed duration such that its duration appeared equal to a flash of 100% Weber contrast. The duration of the test stimulus was increased between runs of trials until observers were no longer able to achieve simultaneity. We believe that the maximal duration allowing for perceived simultaneity is an estimate of the minimal value for persistence of the flash. The assumption underlying this procedure is that the subjective duration of the test stimulus cannot be shorter than its physical presentation time. When test stimulus and flash are perceived as synchronous at onset and offset, the perceived duration of the flash is therefore equal or longer than the physical duration of the test stimulus. The maximal physical duration of the test stimulus allowing for simultaneity will probably underestimate the subjective duration because the test stimulus itself also has visible persistence. However, estimating the visible persistence of the test stimulus is a tricky issue. There is an inverse relationship between the value for visible persistence and at least two other variables: (1) stimulus duration (Di Lollo, 1980; Efron, 1970), but only for stimulus durations up to 130 ms (2) stimulus intensity (Allport, 1968), but not all studies confirmed the latter relation (review in Di Lollo & Bischof, 1995).

4.1. Method

4.1.1. Participants

Four participants including the two authors took part in this experiment.

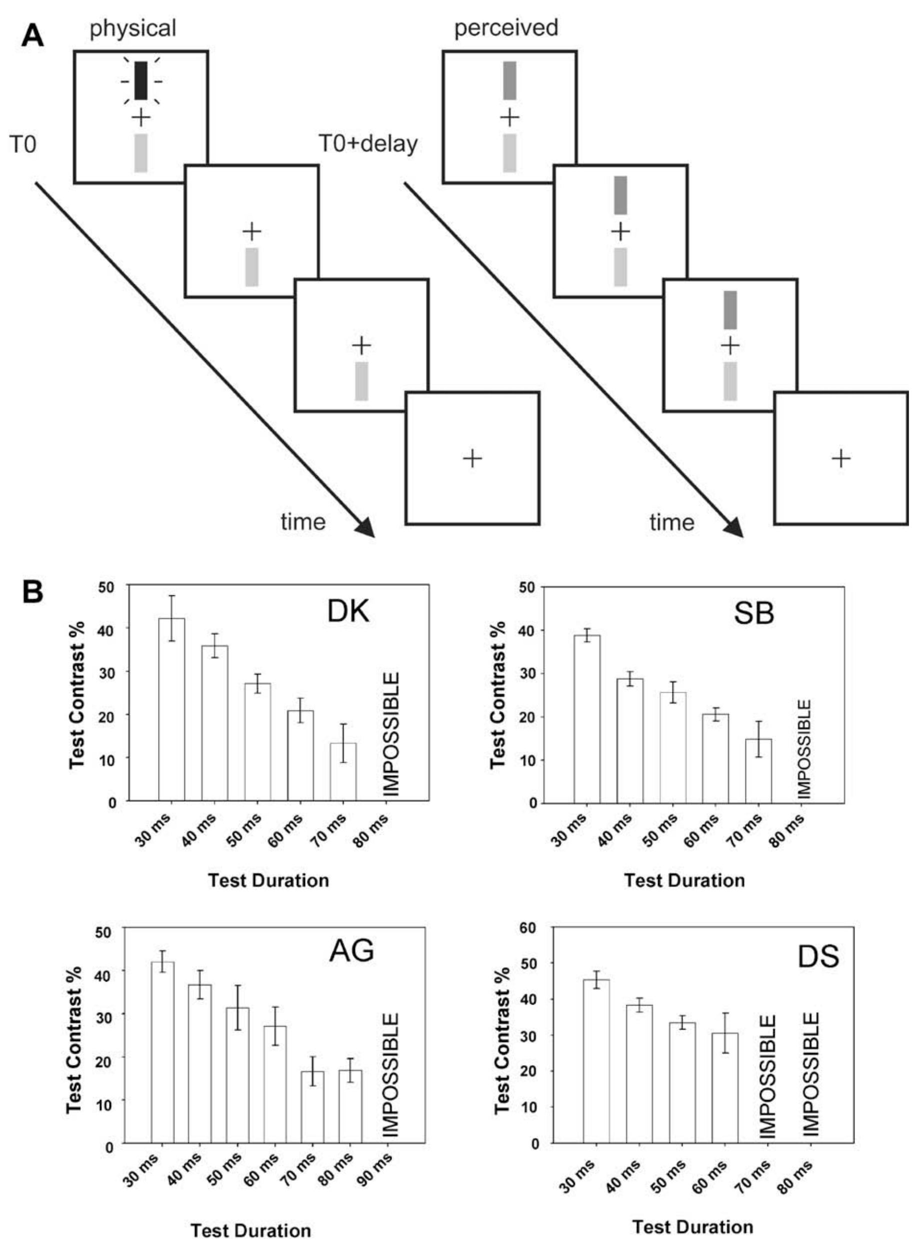

Fig. 3. Stimuli and results of Experiment 4. *Panel A* illustrates the experimental stimuli and hypothesis. The flash (top) had to be matched to a test stimulus of longer duration, but lower contrast (bottom). When the contrast was properly adjusted, the perceived duration of the test stimulus was equal to the perceived duration of the flash (see right sequence), even if the duration of the flash and the test were objectively not the same (see left sequence). *Panel B* shows the Weber contrasts of the test stimulus for different test stimulus durations. At the indicated contrast, the test stimulus had the same subjective duration as the flash. The flash had a Weber contrast of 100%.

4.1.2. Apparatus and stimuli

We displayed two bars that were horizontally aligned below and above a central fixation cross, at an eccentricity of 3.34°. The upper flashed bar was presented for one frame (10 ms) at a contrast of 100% (black). The duration and the contrast of the second bar ("test stimulus") were varied from trial to trial. Six durations of the test stimulus, from 30 to 90 ms in steps of 10 ms were chosen and the contrast of the test stimulus was adjusted for each of these durations in order to perceive both stimuli as having the same duration. The different durations were run in separate blocks of trials.

4.1.3. Procedure

The participants were asked to judge which bar had a longer duration (upper or lower). The luminance of the test bar decreased after each "flash longer" response and increased after each "test longer" response. This enabled us to estimate the perceived duration of a flash by averaging the last eight reversals. For each duration, participants performed 21 reversals of the staircase amounting to a total of ~600 trials.

4.2. Results and discussion

The results of the four participants are plotted in Fig. 3B. By reducing stimulus contrast, stimulus durations up to 60 ms for DS, 70 ms for DK and SB, and 80 ms for AG could be matched to the flash. In accordance with Bloch's law, a much longer stimulus was perceived to have the same duration as the flash if its contrast was reduced. At 90 ms it was impossible for all participants to reduce contrast of the test stimulus to get the same subjective duration as the flash. Thus, the flash persists subjectively for minimally 60–80 ms. In a similar vein, Brenner and Smeets (2008) found that a flash duration of one frame could be matched with flashes up to 30 ms. Further, the adjusted contrasts are in a range in which latency differences are small. The latencies of short stimuli (~50 ms) for contrast from 100% to ~25% are not different (Xiao, Edwards, Bowman, & Oram, 2001). Also, the decrease of reaction times with increasing stimulus contrast is much steeper for contrasts below 10% than it is for larger contrasts (Murray & Plainis, 2003). However, the longer latencies of stimuli below 10% may have contributed to the failure to match longer test stimulus durations to the flash: With low contrast, the subjective duration may have matched, but the onsets were perceived as asynchronous. Therefore, the stimuli were impossible to match. Again, this does not invalidate our conclusion that the minimal visible persistence was 60–80 ms, but we may be unable to determine the upper limit of visible persistence with our method.

Note that our estimation of visible persistence is larger than the perceptual lag in the flash condition of Experiment 1 (0.61° or 36 ms). This suggests that participants do not make the comparison between flash and moving object at flash offset, but midway between onset and offset.

5. General discussion

The aim of the present experiments was to examine the influence of perceptual set and visible persistence on the FLE. We started from the assumption that the perception of a flash is not instantaneous, but extends in time. Therefore, perceptual judgments regarding the flash may occur at variable times depending on the perceptual set adopted by observers. We believe that in a typical flash-lag experiment, observers report the position of the moving object relative to the flash not at its onset, but at a later time. Thus, we expected a diminution of the FLE if participants focus on the perceived onset of the flash. Our results showed that the FLE was abolished when flash trials were mixed with onset trials. This was true for continuous-motion (Experiment 1) and at motion onset (Experiment 2). In our view, the elimination of the FLE shows that we successfully induced observers to change their perceptual set so that they reported the position of the moving object at perceived flash onset. In Experiments 3 and 4, we investigated properties of the moving object and the flash. Experiment 3 showed that the perceived shape of a moving object is deblurred and quite accurate. In Experiment 4, we evaluated the (minimal) perceived duration of a 10-ms flash with 100% contrast. Our results showed that the flash could be matched to a stimulus of lower contrast and longer duration. We estimated the minimal value of flash persistence to be around 60–80 ms.

Hence our results show that the perceptual set adopted by observers determines localization performance despite equal stimulus conditions within a single trial (i.e., flash trials were the same in mixed and pure blocks). A similar point has been made with respect to the Fröhlich illusion (Fröhlich, 1923). In the Fröhlich illusion, observers erroneously localize the onset position of a moving target in the direction of motion. It has been demonstrated that the criterion for reporting the target is an important factor in the illusion. Instructions to accept targets that are less clear decrease the magnitude of the illusion (Geer & Schmidt, 2006). Second, localization of the same stimuli may differ depending on the inter-trial context (Müsseler & Kerzel, 2004; Müsseler, Stork, & Kerzel, 2008). When starting positions are highly variable, the error in the direction of motion decreases. Altogether, these findings show that expectations, strategies, and criteria of the observer contribute to the performance in localization tasks. That is, a part of localization errors results from biased perceptual report and not from erroneous perception. Accounts in terms of low-level motion processing therefore have to be revised to incorporate high-level factors, such as decision time and perceptual set.

5.1. Action and luminance dependence of the FLE

Perceptual set may explain action-related modulations of the FLE. The FLE is reduced when the flash is perceived as consequence of one's own actions (Lopez-Moliner & Linares, 2006). It may well be that this is caused by better anticipation of flash presentation which shifts the decision time toward flash onset.

In addition to perceptual set, visible persistence does a good job of explaining some flash-lag related phenomena. For instance, it has been demonstrated that increasing the luminance of the flash decreased the FLE (Purushothaman et al., 1998). The dependence of the FLE on flash luminance could be explained by the inverse intensity effect: Increasing the intensity of the stimulus diminishes visible persistence (Allport, 1968; Coltheart, 1980). Hence, high intensities of a flash reduce the visible persistence so that the perceptual lag is reduced.

Originally, it has been argued that the short latency of high contrast (or high-luminance) stimuli may turn the flash-lag into a flash-lead (Purushothaman et al., 1998). In our visible persistence account, the implicit assumption was that the latencies of the flash and moving object are the same. In other words, the moving object and the flash should be perceived at the same time (see Fig. 1A). However, even if the latencies of stationary and moving objects were different, this would not change our account, because even a flash that is perceived earlier than the moving object will show some persistence. If the latency of the flash is such that it precedes the moving object, perceptual set may nonetheless change the magnitude of the lead.

5.2. Motion reversal paradigm

In the motion reversal paradigm, the flash was displayed at various positions before/after motion reversal, but the moving objects are never seen to overshoot the flash position (Whitney & Murakami, 1998). Eagleman and Sejnowski (2000a) presented a moving ring that reversed its direction some time after flash onset. If the reversal occurred 80 ms after the flash, the FLE remained unchanged. For reversals occurring 26 ms after the flash, the FLE was abolished. Finally, for reversals occurring between 26 and 80 ms after the flash, the FLE increased with increasing reversal time. To explain this pattern of results, the authors suggested that the flash resets the motion integration processes. However, simple visible persistence is a viable alternative to this account. If motion reversal occurs after flash persistence, the FLE would remain constant because perceptual judgments occurred before the object reversed direction. In contrast, when the perceived motion reversal occurs before the flash has faded the FLE will increase with reversal time because the distance between the persisting flash and the moving object at decision time is larger.

5.3. Position persistence vs. visible persistence

Krekelberg (2001) introduced the concept of position persistence which seems related, but is different from visible persistence. Position persistence shares some properties with visible persistence such as the inverse duration effect (at short duration the persistence is longer than at longer durations) but is not affected by the intensity of the object or the background (Krekelberg, 2001) as it is commonly the case with visible persistence. According to the author, position persistence differs from visible persistence in the sense that position persistence is the persisting position signal which represents the offset position of an object that has disappeared. To explain the FLE, the authors postulated a temporal integration hypothesis. When the positions of a moving object and a flash have to be compared, these relative positions are estimated by a temporal averaging process. For the flash, the average position is the same as its actual position, while there is a displacement for the moving object. Thus, in contrast to a simple visible persistence account, the offset position of the flash is not compared to the actual position of the moving object at a certain time. To relate their results to the visible persistence account, Lappe and Krekelberg (1998) introduced the parameter of the visibility fraction which defines the duration of stimulus visibility and regroups the parameter found to be important in visible persistence. This parameter is given by the product of flash duration and frequency. However, the theory has difficulty in explaining how focusing participants' attention on the flash onset would eliminate the averaging process both during ongoing motion and at motion onset.

5.4. The role of spatial cues

It has been demonstrated that spatial or temporal cues that indicate the flash position before motion onset reduce the FLE (Baldo et al., 2002; Brenner & Smeets, 2000; Eagleman & Sejnowski, 2000b; Vreven & Verghese, 2005). However, there is no consensus on the mechanism underlying the reduction of the FLE with predictable flashes: Brenner and Smeets (2000) suggested that knowledge of the flash location turned the task from a relative localization task into a temporal order judgment task (see also Bedell, Chung, Ögmen, & Patel, 2003). Baldo et al. (2002) argued that the time to move attention to the flash location was reduced and Eagleman (2000b) proposed that predictable flashes lead to less devaluation of pre-flash samples.

In contrast, we believe that cueing effects arise from changes in perceptual set in combination with the extended perception of the flash. Because the flash persists for some time, the moment of perceptual judgment could be the perceived onset, offset or sometime between on- and offset. The role of advance knowledge about the location of the flash may be to induce observers to report relative position at perceived flash onset. With unpredictable flash locations, observers may not report the perceived flash position at flash onset because the position signal is subjectively unreliable. Therefore, observers wait for more position samples to arrive before reaching a perceptual decision. However, when they know where the flash will appear, perceptual judgments may focus on perceived flash onset because the position signal seems more reliable.

In conclusion, perceptual set and visible persistence are crucial elements to explain the FLE. In typical FLE paradigms where there is certainty about which stimulus will be presented (i.e., a flash), a perceptual set is adopted that results in delayed perceptual decisions. In particular, observers make perceptual judgments during the visible persistence of the flash and not at perceived flash onset. However, our data show that a variable trial context may change the perceptual set adopted by observers so that the decisional lag is eliminated. Contrary to previous results, we predict that masking reduces the FLE because it decreases visible persistence. As outlined in the introduction, future tests of this hypothesis would need to better control confounding variables.

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