

Turning the corner with the flash-lag illusion

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ABSTRACT

Previous attempts to measure localization bias around a right-angle turn (*L-trajectory*) have found either no spatial bias off the trajectory (Whitney, Cavanagh, & Murakami, 2000) or a bias, in different experiments, both ‘inside’ and ‘outside’ the trajectory (Nieman, Sheth, & Shimojo, 2010). However, Eagleman and Sejnowski (2007) presented data showing that the perceived location of a brief feature on two moving stimuli could be predicted from the vector sum of their directions after the feature appeared. Such a vector sum with an L-trajectory could predict that the perceived position before the turn should be biased ‘sideways’ off the trajectory, in the direction of the final motion. With stimuli that particularly facilitated accurate vernier judgments, and measuring bias via the flash-lag illusion, this is indeed what we observed. Our data thus favour Eagleman and Sejnowski’s (2007) supposition. Further, the bias occurred before the change in direction, rather than after it, supporting the contention that it is motion after a point being sampled that affects its perception (Bachmann, Luiga, Pöder, & Kalev, 2003; Eagleman & Sejnowski, 2007; Krekelberg & Lappe, 2000; Nieman et al., 2010).

Keywords: localization, spatial projection, flash-lag, illusion, L-trajectory

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1. Introduction

Two prominent spatial projection models of visual localization for moving objects differ mainly with regard to which part of the motion trajectory they assume is critical for localizing the object at a particular point in its trajectory. Nijhawan (2008) maintains that it is motion before that point that is crucial, whereas Eagleman and Sejnowski (2007) claim it is motion afterwards that is most influential. Whilst the debate has been most concentrated around these protagonists, it should also be acknowledged that a number of other researchers have maintained that it is motion after the assayed point that is pivotal (Bachmann, Luiga, Pöder, & Kalev, 2003; Krekelberg & Lappe, 2000; Nieman et al., 2010).

Claims and counter-claims for these positions have mostly revolved around findings with special motion trajectories within the *flash-lag* paradigm (Eagleman & Sejnowski, 2007; Nijhawan, 2008, and see also commentaries following the latter) – if a moving stimulus moves smoothly and continuously across the field of view (*continuous trajectory*) and a flash appears instantaneously adjacent to it and aligned with it, then the flash is perceived to spatially lag the moving stimulus in its direction of motion (Nijhawan, 1994).

The special trajectory that has received most attention is the *onset trajectory*; the moving stimulus suddenly appears and moves off at the same instant that the flash appears. Most studies have found the illusion with this trajectory to be either not different from that with a continuous trajectory (Eagleman & Sejnowski, 2000; Gauch & Kerzel, 2008), or slightly (significantly) larger (Chappell, Hine, Acworth, & Hardwick, 2006; Müsseler, Stork, & Kerzel, 2002; Ögmen, Patel, Bedell, & Camuz, 2004; Rizk, Chappell, & Hine, 2009). As there is no motion before the location of the moving stimulus at the time of the flash with an onset trajectory these findings would seem to strongly favour accounts claiming that it is motion after the flash which most influences localization (Bachman et al, 2003; Eagleman & Sejnowski, 2007; Krekelberg & Lappe, 2000; Nieman et al., 2010). However, Nijhawan (2008) has countered proposing that

very fast processes based on sampling the very beginning of the motion could plausibly allow his model to account for the onset trajectory findings.

In any case, there are reasons to doubt that the onset trajectory provides a ‘clean’ test of the localization processes at work with a continuously moving stimulus. In addition to the studies cited above finding a slightly larger illusion with this trajectory, Patel, Öğmen, Bedell, and Sampath (2000) found a dramatic difference using a bright flash and a dim moving stimulus. They reported a significant flash-lag illusion with the onset trajectory, and a null illusion with continuous trajectory – contributing to the latter were significant flash-*lead* illusions for a number of subjects. Chappell, Potter, Hine, Mullen and Shand (2013) recently reported a similar finding when the moving stimulus was made equiluminant with its background, and immersed in luminance noise. In fact this manipulation (compared to a luminance defined moving stimulus) increased the illusion with an onset trajectory, whilst it decreased it with the continuous trajectory. Further, Linares, López-Moliner and Johnston (2007) found a significantly smaller illusion with the onset trajectory, than with the continuous one. These findings suggest other processes at work in the onset trajectory, perhaps related to backward masking of the initial part of the moving stimulus trajectory by its later appearances (see also, Kanai, Sheth, & Shimojo, 2004; Kirschfeld & Kammer, 1999), and/or setting up a representation for a new stimulus (Chappell et al., 2006; Enns, Lleras, & Moore, 2010; Kanai, Carlson, Verstraten, & Walsh, 2009; Yantis, 1996). There is, then, ambiguity as to how much of the illusion with an onset trajectory is due to the same processes underlying localization with a continuous trajectory.

The *offset trajectory*, where the moving stimulus disappears as the flash is displayed, should avoid the backward masking and representational set-up issues. The usual finding of no illusion here (Chappell et al., 2006; Whitney, Murakami, & Cavanagh, 2000) again supports Eagleman and Sejnowski’s (2007) theory, there being motion before the point in question to support projection, but none after it. Here Nijhawan (2008) counters that the offset transient

confounds interpretation, triggering a fast shut-down of the projection process. And indeed Maus and Nijhawan (2006; 2009) found that if the moving stimulus gradually faded an illusion was evident. It is also true that Fu, Shen and Dan (2001) found an overshoot in perception of the offset trajectory in a flash-lag paradigm with low spatial frequency (blurred) stimuli, as did Kanai, Sheth and Shimojo (2004) when the stimuli being compared were widely separated. We will return to consider these stimulus parameters in the Discussion.

In the *reversal trajectory* the moving stimulus suddenly reverses direction. Here the illusion suggests that not all of the trajectory around the reversal point is perceived – the flash has to be displayed back along the trajectory in the final direction of motion in order to appear aligned with the moving stimulus (Chappell et al., 2006; Eagleman & Sejnowski, 2000; Shen, Zhou, Gao, Liang, & Shui, 2007; Whitney, Murakami, & Cavanagh, 2000). Again this is consistent with motion after the reversal determining localization, rather than that before. But again the reversing stimulus may mask itself (Chappell et al., 2006), introducing another process confounding the localization processes that operate for a smoothly moving stimulus.

Is there a trajectory or are there trajectories that can provide a more unambiguous test of these theories? Brenner and Smeets (2000) and Whitney, Murakami, and Cavanagh (2000) both measured the flash-lag illusion at a range of time points before and after a moving stimulus suddenly increased or decreased its speed. Localization with such a trajectory may not be affected by the masking process and should not be affected by representation set-up processes. They found that the flash-lag magnitude began changing to be commensurate with the final speed (they found its magnitude to be roughly proportional to speed) 60 to 80 ms before the speed change occurred, which suggests that if spatial projection is operating, its output is based on motion after the flash. This trajectory does seem to provide a test freer of the interpretational difficulties of the others reviewed above.

Finally, Whitney, Cavanagh and Murakami (2000) measured the flash-lag illusion with what we will term an *L-trajectory* – the stimulus suddenly changes direction by 90° and the illusion was measured at various places around the turn. With the first version of Nijhawan's theory one might expect an overshoot in the initial direction, before perception begins to track the final direction. The later version might suppose that even the right-angle turn would provide enough transients to quickly turn off projection at the turning point, and thus yield veridical perception of the path of travel.

Considering Eagleman and Sejnowski's (2007) theory, the interesting prediction would be that motion after the turn would influence perception of the position *before* the turn. There are two possibilities here – the influence could operate 'around the corner', rather like a string operating over a pulley at the corner. In this case perception would still follow the displayed path.

However, Eagleman and Sejnowski (2007) described an experiment that motivates another possibility. Two square white stimuli were displayed in apparent motion – they appeared at a series of stations on straight trajectories across the display, both travelling diagonally upwards so that their trajectories crossed near the centre of the display, and coincided at one station there. At just that station the displayed square was blue. A blue square was perceived not on either trajectory, but vertically above the meeting point. Eagleman and Sejnowski (2007) concluded that the spatial projection mechanism had vectorially added the motion vectors for the two trajectories. A similar vector addition with an L-trajectory, combined with the assumption that motion after the point being localized contributes to the localization, would lead to the prediction of bias off the trajectory, on its concave side.

In their experiment, Whitney, Cavanagh, and Murakami (2000) concluded that the moving stimulus was never perceived away from the path it actually followed, but flashes always lagged

it along this path – they posited this to be due to a longer latency to perception for the flash. Their findings were thus in agreement with the later version of Nijhawan’s (2008) theory.

In a series of experiments, Nieman, et al. (2010) also used an L-trajectory, but instead of comparing with a flashed stimulus, points on the moving stimulus’ trajectory were compared with stationary persisting reference ‘landmarks’. Depending on stimulus parameters they found bias to perceive the moving stimulus either ‘inside’ or ‘outside’ (the concave side of) the displayed trajectory. We will describe Nieman et al.’s (2010) results, and more details of the experiments in both these works, in the Discussion, when we seek to explain differences between their results and ours.

In our experiment the moving stimulus moved vertically downwards before turning 90° and following a horizontal trajectory. As discussed above, if the transients associated with changing direction affect Nijhawan’s (2008) spatial projection process, then no illusions might be predicted around the turn. To the extent that they do not, an overshoot of the vertical part of the trajectory should be in evidence.

On the other hand, if motion after a point being localized is critical (Bachmann et al., 2003; Eagleman & Sejnowski, 2007; Krekelberg & Lappe, 2000; Nieman et al., 2010), and particularly if projection contributions are vectorially added (Eagleman & Sejnowski, 2007), then as the moving stimulus approaches the turning point on its vertical trajectory it should be perceived off the displayed trajectory, in the direction of final motion – ‘inside’ the L, on its concave side.

Given the conflicting results from these two experiments, and the potential the L-trajectory has to provide more converging evidence discriminating between spatial localization theories, we present more data with this trajectory, using stimuli that we contend are more conducive to accurate vernier judgments than those used in the two papers above, and thus likely to yield more accurate estimates of the illusions with this trajectory.

2. Method

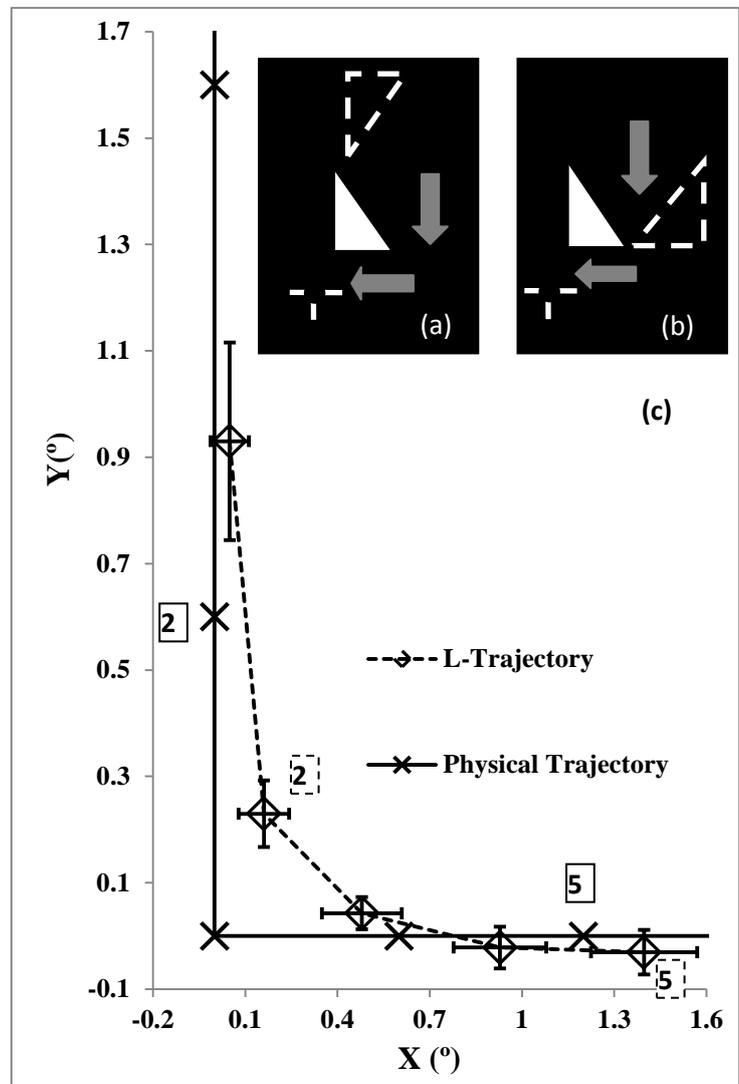
2.1. Subjects

Nine subjects (mean age = 26.25 years) volunteered for course credit.

2.2. Stimuli and Procedure

The moving stimulus had speed 12°/s, and in L-trajectory conditions travelled vertically downwards before turning left- or rightwards (randomly) for the horizontal portion of its trajectory (Fig. 1 [a], [b]).

Fig. 1. Our stimuli and data. The solid triangle is the moving stimulus (initial direction downwards, final direction to the left illustrated – grey arrows), the flash is the dashed triangle. The moving stimulus always had the same orientation, that of the flash differed across the judgement types, as shown. (a) For horizontal judgments, (b) For vertical judgments, and (c) Data (collapsed across final horizontal direction of motion). Second and fifth physical and perceived points labelled (2, 5), dashed boxes for perceived). Error bars are 95% confidence intervals.



Both moving stimuli and flashes (the latter dashed in Fig. 1 [a] and [b]) were white triangles ($2^\circ \times 2^\circ$, $\sim 115 \text{ cd/m}^2$, background $< 0.3 \text{ cd/m}^2$, refresh rate 60 Hz.), with the moving stimulus shape facilitating accurate vernier judgments in both vertical and horizontal directions. In different conditions, the flash occurred zero, three or eight frames before the moving stimulus changed direction, or three or six frames after this event.

We also tested a vertical offset trajectory, terminating at the end of the downward leg, and a horizontal onset trajectory, corresponding to the horizontal leg of the L-trajectory. Only vertical and horizontal judgements, respectively, were made for these trajectories. Vertical and horizontal judgments were made in separate blocks, and a range of stimulus offsets in the direction being tested were displayed, with subjects indicating if the flash was above/below, or left/right, of the moving stimulus. Subjects were carefully instructed to use the appropriate points on the triangles when making these judgments. Testing was carried out over three to four sessions of 50-60 minutes each, with provision for rest breaks.

For all of the conditions described below, when referring to the position of the moving stimulus or the flash, we mean the position of the tip of the triangle being used for the spatial judgement. The flash's position was determined first, as described below. The frame on which the flash appeared we term the 'critical frame', and for this frame the moving stimulus was placed at the appropriate offset from the flash, according to an adaptive method of fixed stimuli. The turn point would then be found the appropriate number of frames from this critical frame, and the rest of the trajectory mapped out, all of this being done before the trial commenced.

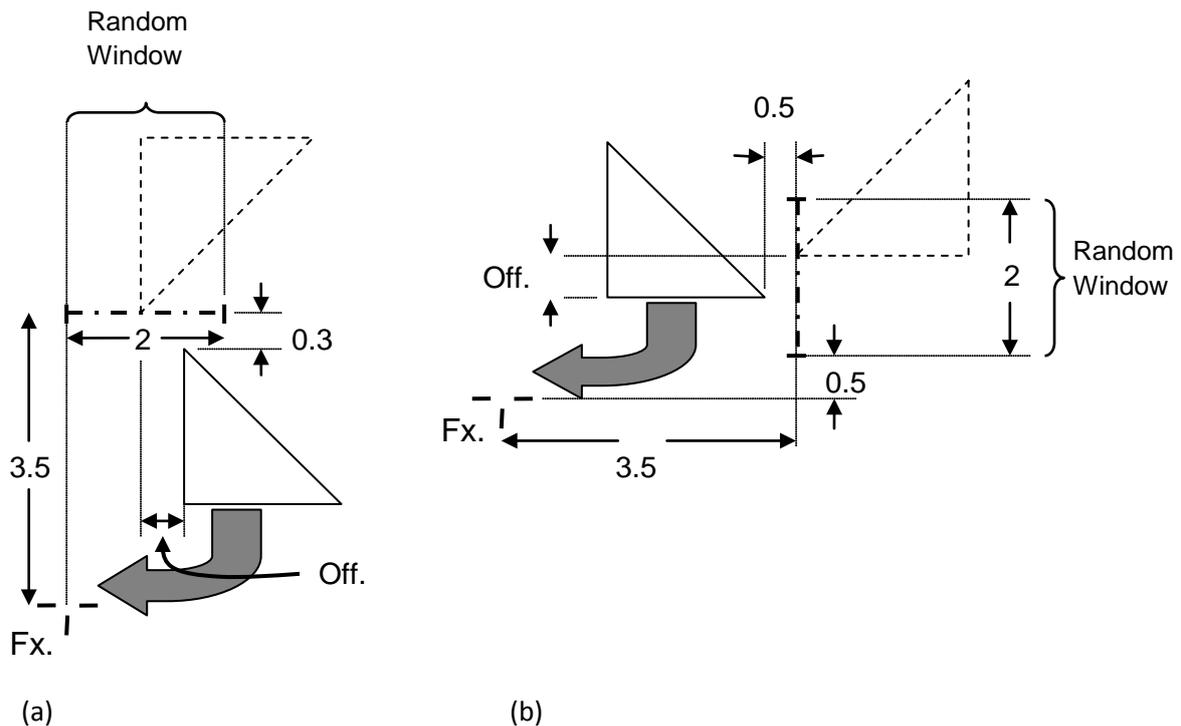


Fig. 2. Detail of our stimuli for (a) horizontal judgements, and (b) for vertical judgements. Fx. = Fixation point. The flash (dashed triangle) was first placed in a random window displaced relative to fixation as shown. The moving stimulus (full triangle) was then placed at the appropriate offset from the flash, in the frame in which the flash appeared. The rest of the moving stimulus' trajectory, both before and after the flash, was traced from there (grey curved arrow). Not to scale, all dimensions are in degrees.

Fig. 2 graphically illustrates the stimulus arrangement for horizontal and vertical judgements, with the exception of the conditions detailed below. For horizontal judgements the flash's lower tip was 3.5° above fixation, and horizontally it was in a random window 2° wide, centred 1° horizontally from fixation in the opposite direction to the final motion. Unfortunately in the 'three frames after the direction change, horizontal judgements' condition the flash was 1° lower, or 2.5° above fixation, due to an oversight in setting parameters. However, comparisons between this condition and others are not of any interest. Once the position of the flash was established, the moving stimulus was positioned relative to it in the critical frame, with a horizontal offset determined by the adaptive method of constant stimuli. An initially generic set

of offsets was adapted for each subject/condition as testing proceeded. The vertical separation for horizontal judgements was $.3^\circ$. The rest of the trajectory was then traced out from this moving stimulus position, with a change of direction at the appropriate frame offset.

For the first two conditions for vertical comparisons, on the downwards leg of the L-trajectory the point of the flash nearest the moving stimulus was 3.5° horizontally from fixation, again in the direction opposite the final direction of motion, whilst in the remaining conditions it was 3.2° horizontally from fixation, in that direction also. The latter adjustment was made so that the flash appeared closer 'behind' the moving stimulus than it otherwise would have, to facilitate the vertical judgment. The flash was positioned in a vertical random window 2° wide, centred 1.5° above fixation. For the vertical comparisons block the vertical part of the moving stimulus' trajectory was always 3° horizontally from fixation (measuring to the point on the moving stimulus nearest horizontally to the flash), in the direction opposite to the final direction of motion. The desired vertical offset between flash and moving stimulus, again determined by the adaptive method of fixed stimuli, then positioned the moving stimulus vertically in the critical frame, and the remaining vertical parameters of the motion trajectory followed from this.

Note that for both horizontal and vertical judgements the turning point could be in substantially different position, both horizontally and vertically, in different conditions, depending on the frame offset, e.g an 8 frame offset would move it by 1.6° .

3. Results

The solid black line in Fig. 1 (c) represents the path the moving stimulus with an L-trajectory followed (data have been collapsed across leftwards and rightwards moving trials). The crosses indicate where the moving stimulus was when the flash was displayed, in the various conditions with this trajectory. An adaptive method of constant stimuli and logistic regression yielded PSEs for each subject-condition. The means of these in both the horizontal

and vertical directions have been used to locate the L-trajectory data points relative to the crosses (see Fig. 1 [c]). They indicate where the flashes needed to be displayed in order to appear aligned with the moving stimulus, when it was located at one of the crosses.

The first (top-left) point on the L-Trajectory line thus indicates a significant vertical flash-lag illusion (magnitude = $.67^\circ$, significance evident from the 95% confidence interval), but no significant horizontal bias. The second data point with the L-trajectory again indicates a significant flash-lag illusion in the vertical direction. Of more interest, there is also a significant horizontal bias in position perception, occurring three frames, or 50 ms. *before* the moving stimulus reached the turn-point. This bias is significantly larger than that (non-significant bias) found 8 frames before the turn-point ($t[8] = 6.08, p = 2.95 \times 10^{-4}, d = 2.03$). For all subjects the effect was in the same direction at minus three frames.

The third point on the L-Trajectory line indicates the perceived position of the turning point. There was a significant flash-lag illusion in the final horizontal direction of motion, as well as a significant flash-lead in the vertical direction. This vertical magnitude was significantly different to that with the vertical offset trajectory illusion ($t[8] = 5.43, p = .001, d = 1.81$), the latter being an overshoot, but not significantly different from zero ($M = .037^\circ, CI_{95} = [-.014, .088]$) (cf. Chappell et al., 2006; Whitney, Murakami, & Cavanagh, 2000). The last two points on the L-Trajectory line simply indicate significant flash-lag illusions in the horizontal direction.

The horizontal onset trajectory produced a significant illusion ($M = .799^\circ, CI_{95} = [.765, .834]$), and significantly bigger than that with horizontal judgments at the turning point of the L-trajectory ($t[8] = 5.14, p = .001, d = 1.71$) (cf., Chappell et al., 2006; Müsseler et al., 2002; Ögmen et al., 2004; Rizk et al., 2009).

4. Discussion

We note first of all that the null horizontal illusion found 133 ms. before the moving stimulus changed direction (minus eight frames), and the null vertical illusions found 50 and 100 ms. (three and eight frames) after the turn, provide assurance that there were no significant biases intrinsic to the stimulus arrangement and shapes. The significant illusion of most interest – the horizontal one occurring 50 ms (minus three frames) before the moving stimulus changed direction, was also significantly bigger than that at minus 133 ms. Before considering the theoretical implications of our findings, we compare them with others’.

4.1. Comparison with previous studies

Our finding of significant bias off the L-trajectory (the second and third points) contrasts with Whitney, Cavanagh, and Murakami’s (2000) finding that perception veridically followed the physical path of their stimulus on an L-trajectory, albeit with a temporal lag. Whitney, Cavanagh, and Murakami’s (2000) moving stimulus consisted of two squares $.54^\circ \times .54^\circ$, always one above the other, whose closest sides were separated by 1.26° , and their flash was a circle of $.18^\circ$ diameter displayed between them. Hence, although the stimuli were reasonably close in this study, their shapes did not facilitate accurate spatial judgements,

Nieman et al. (2010) used a circular moving stimulus $.87^\circ$ in diameter in Experiments 1a and 1b, and $.06^\circ$ in Experiments 5a and 5b, that moved diagonally downwards, and then diagonally upwards from a 90° turn. Nieman et al.’s (2010) bias in these experiments was outside the trajectory – in their most precise Experiments 5a and 5b equivalent to being up and to the left of our third testing point. Only in their last experiment, when fixation was moved inside the trajectory, did Nieman et al. (2010) find bias inside the trajectory – our fixation was usually outside the trajectory. The horizontal position of the turning point was compared with a fixation 3.4° below the turning point, and the vertical with persisting ‘hash marks’ 4.8° horizontally distant.

The first point to make, then, is that Nieman et al.'s (2010) were not flash-lag experiments. The turning point's perceived position was compared to that of stationary markers that were displayed for the duration of the trial – what we have previously termed 'landmarks' (Chappell et al., 2006). Chappell et al. (2006) found a significantly different illusion with this kind of comparison stimulus, compared to that with a comparison flash, for both onset and reversal trajectories (see also Chappell et al., 2013).

The second point is that the quite large distances between stimuli being compared could not be conducive to accurate judgments. In their Experiments 1a and 1b, illusions in each direction were approximately $.25^\circ$, a tiny fraction of the distance between their stimuli, and less than one third of the size of their moving stimulus. When they reduced their moving stimulus size to $.06^\circ$, thus presenting a stimulus more conducive to accurate judgments, their horizontal bias reduced to $.16^\circ$, and their vertical bias became non-significant. For comparison, our horizontal illusion for the second position on the L-trajectory had a similar magnitude to theirs with the smaller stimuli, but our stimuli were only separated by $.3^\circ$.

We noted in the Introduction that when Kanai et al. (2004) used widely separated comparison stimuli they obtained a significant flash-lag illusion with an offset trajectory. They noted that this might be attributed in part to more uncertainty regarding the positions of the stimuli. Consistent with this, Fu et al. (2001) obtained a similar result using low spatial frequency (blurred) stimuli. Whilst we concede that by the nature of a moving stimulus there is likely to be some uncertainty regarding its position at a particular time, our goal was as far as possible to reduce (relative) positional uncertainty, so as to investigate other factors that might contribute to localization.

Our stimuli, with sharp points generally not separated by more than 0.5° in the direction orthogonal to the judgement being made, were more likely to provide accurate estimates of perceptual biases than those used in either of the experiments discussed above. The stimulus

differences identified would seem adequate to account for different results – we will say a little more about the direction of differences as we discuss Theoretical implications below.

4.2 Theoretical implications.

Addressing the control conditions first, the vertical offset trajectory yielded a null illusion, in line with other studies with a sharp offset, and where the moving stimulus and flash were close together (Chappell et al., 2006; Whitney, Murakami, et al., 2000). On the other hand, the horizontal onset trajectory yielded a significant illusion, and significantly bigger than that from the horizontal judgment at the turning point of the L-trajectory. As previously (Chappell et al., 2006), we suggest two possible contributors to the larger illusion with onset trajectory. Firstly, backward masking of previous exposures of the moving stimulus by its later appearances, combined with a greater fragility of the representation of the moving stimulus just after it first appears (Kirschfeld & Kammer, 1999) might imply that a later position for the moving stimulus is compared with that of the flash. Secondly, and related, delays associated with setting up a new representation for the moving stimulus (Chappell et al., 2006; Enns et al., 2010; Kanai et al., 2009; Yantis, 1996) may also contribute.

Such considerations also apply to analysing the Fröhlich illusion, where the point of appearance of a suddenly appearing moving stimulus is compared to that of a stationary and persisting landmark stimulus (Kirschfeld & Kammer, 1999). However, we have previously demonstrated (Chappell, et al., 2006; Chappell, et al., 2013) that in within-subject comparisons Fröhlich and flash-lag illusions with onset trajectory can have dramatically different magnitudes (Fröhlich illusions were null in Chappell et al., 2013). In the present work we hope that the L-trajectory avoids the need to consider processes engaged when a stimulus first appears, thus allowing a ‘purer’ measure of localization processes.

The second point on the L-trajectory line is of most interest theoretically. Its position supports Eagleman and Sejnowski’s (2007) contention that sensed motions in various directions

can be added vectorially to bias the perceived position of a particular moving stimulus. In our case, though, it was motions of one stimulus at different times – vertical motion before the turn, and horizontal motion after it both contributed to the bias.

More generally, our data support their contention, and that of others (e.g., Bachmann et al., 2003; Krekelberg & Lappe, 2000; Nieman et al., 2010), that it is motion occurring *after* the position currently being perceived that biases its position. In our case horizontal motion occurring more than 50 ms after the moving stimulus occupied the position being probed is biasing its position in a horizontal direction. Similarly, although we cannot specify a time-course for it, the perceived position of the moving stimulus at the turning point is being biased in both a horizontal and a vertical direction by the horizontal motion occurring after the turning point. Correspondingly, our data speaks against Nijhawan's (2008) spatial projection theory, which posits that it is motion occurring before the position being probed that biases its position perception. Our data is consistent with Brenner and Smeets's (2000) and Whitney, Murakami, and Cavanagh's (2000) findings that, for a moving stimulus that suddenly changed its speed, the flash-lag magnitude began changing to be commensurate with the final speed up to 80 ms before the speed change occurred.

The three key components of Eagleman and Sejnowski's (2007) theory; the spatial biasing effect of motion on localization, the critical role of motion after the point being assayed, and the vectorial addition of motion influences in the biasing process suggest in our estimation that it most naturally accounts for our data. However, a temporal integration theory (Krekelberg & Lappe, 2000) in which spatial integration was occurring in two dimensions would also be a good candidate. Also, in attempting to explain the difference between Fröhlich and the flash-lag illusion with onset trajectory, alluded to above, one process which Chappell et al. (2006) considered was attention capture (Yantis, 1996) by the flash, and indeed Sarich, Chappell, and Burgess (2007) presented data supporting this hypothesis. Positing that the flash occurring 50

ms. before the moving stimulus changed direction captured attention away from the moving stimulus, and that attention did not return to it and allow localization to be finalized until it had turned the corner, would provide another alternative account of our data.

Nieman et al. (2010), with a stimulus generally travelling diagonally downwards to a turn point, and then diagonally upwards from it, concluded that different processes were underlying the vertical and horizontal biases they measured. Because moving fixation inside the trajectory reversed the vertical bias, they concluded it was due to foveal attraction (e.g., Sheth & Shimojo, 2001). Of course this can only work if one stimulus is supposed to be more prone to attraction than the other (of the pair being compared). In our experiment only the third point on the L-trajectory evinced any vertical bias, and the moving stimulus would have to be more attractive than the flash to explain our result. It is not clear why this should be so. Of the available theories temporal integration (Krekelberg & Lappe, 2000), assuming there is a separate vertical integration (or an integration in two dimensions) that includes points before the turn, seems most promising in accounting for this data point. Essentially a spatial smoothing of the trajectory in two dimensions could be achieved in this way, and it would be consistent with the undershoot found with a reversal trajectory.

Nieman et al. (2010) also found that if they displayed just an offset trajectory, down and to the right, they obtained an overshoot. Since this entailed a horizontal bias in the opposite direction to that found when the full L-trajectory was displayed, they concluded that motion after the turn was critical for the horizontal component of their illusion. However, unlike Eagleman and Sejnowski (2007) and others' (Bachmann et al., 2003; Krekelberg & Lappe, 2000; Nieman et al., 2010) theories that predict bias in the final direction of motion, they concluded that the perceived location of the turn-point was 'repulsed' by the later trajectory. Their effect is indeed reminiscent of onset repulsion, where the location of a suddenly appearing stimulus is mis-

located backwards before its appearance point (Thornton & Hubbard, 2002). However, when they directly tested for onset repulsion with an onset trajectory it was not present.

As to the processes that might underlie this repulsion, they suggest that once the turn point has been registered, processes attempt to locate it, but the moving object is tracking on as this occurs, and new position estimates are becoming available. At some level there is an ‘awareness’ that wherever the turn point was, it was further back from the points currently being experienced. In some way an over-compensation occurs, leading to the ‘repulsed’ estimate. If this account should be correct, then we conclude that they have identified stimulus parameters that reveal these processes, whilst our experiment has revealed other processes at work.

As noted, Whitney, Cavanagh, and Murakami (2000) concluded that the flash was merely temporally delayed in perception, compared to the moving stimulus. Indeed accounts of the flash-lag and other illusions have been characterized as to whether they postulate spatial or temporal bias (e.g., Eagleman & Sejnowski, 2007; Whitney, 2002). For a continuous trajectory with smooth motion we would suggest this is not a meaningful distinction. With an L-trajectory we found a bias off the trajectory 50 ms. before the turn, in the direction of the final motion. Clearly a temporal bias cannot explain our data – perception was unambiguously spatially biased away from the physical trajectory.

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