Vision Research 49 (2009) 2201–2208

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Effect of motion smoothness on the flash-lag illusion

Jacques K. Rizk, Mark Chappell, Trevor J. Hine *

Applied Cognitive Neuroscience Unit, Griffith Institute of Health and Medical Research and School of Psychology, Griffith University, Mt Gravatt, Qld 4122, Australia

ARTICLE INFO

Article history:
Received 20 March 2008
Received in revised form 10 June 2009

Keywords:
Flash-lag illusion
Optimal apparent motion
Smooth
Discrete
Sampled

ABSTRACT

Two flash-lag experiments were performed in which the moving object was flashed in a succession of locations creating apparent motion and the inter-stimulus distance (ISD) between those locations was varied. In the first ($n = 10$), the size of the flash-lag illusion was a declining non-linear function of the ISD and the largest reduction in its magnitude corresponded closely to the value where observers judged the continuity of optimal apparent motion to be lost. In the second ($n = 11$) with large ISDs, we found the largest illusions when the flash initiated the movement, and no effect was observed when the flash terminated the movement. The data support motion position biasing or temporal integration accounts of the illusion with processing predominantly based on motion after the flash.

1. Introduction

A moving object appears to spatially lead a flashed object when both are displayed in physical alignment. For over a decade, this flash-lag illusion (FLI) has received considerable attention from researchers who have proposed at least five theories in explanation (see reviews by Eagleman & Sejnowski, 2007; Krekelberg & Lappe, 2001; Nijhawan, 2008; Schlag & Shlag-Rey, 2002; Whitney, 2002; Öğmen, Patel, Bedell, & Camuz, 2004). Virtually all research into the flash-lag illusion has required observers to compare the position of a stationary, briefly presented stimulus to the position of a moving object that may well be reversing or changing velocity, but whose movement otherwise appears smooth. The moving object typically differs from the flash in two ways: duration of visibility and motion. Surprisingly, few experiments have manipulated these properties specifically to explore the separate effects of motion and motion perception on the flash-lag illusion. Recently, Cantor and Schor (2007) did vary the duration of flashed and moving stimuli and concluded that the magnitude of the flash-lag illusion reaches a ceiling when the moving stimulus has appeared for at least 120 ms, but the illusion disappears for 'flashes' lasting 80 ms or more.

In research most closely related to the experiments reported here, Vreven and Verghese (2005) used 'strobed' motion (that is, *sampled* in space and time) to separate the effects of motion signal strength and predictability on the magnitude of the FLI. In one condition, they presented the flash alongside a moving object that was actually flashed for one frame (13 ms) in a sequence of positions, or 'stations', separated by 200 ms and more than 4° along its trajectory (the *interstimulus distance* or 'ISD'). The magnitude of the flash-lag illusion was reduced to nearly zero. Eagleman and Sejnowski (2007) have also used sampled motion in a different experimental paradigm – that used to measure the Fröhlich illusion (Kirschfeld & Kammer, 1999; Müsseler, Stork, & Kerzel, 2002; Whitney & Cavanagh, 2002). They measured the perceived misalignment between the location of the appearance of a 'moving' object and the location of a stationary landmark that appeared at the same time as the moving object and remained visible for the duration of movement. When the 'moving' object was flashed at just two positions with a stimulus onset asynchrony of 67 ms and separated by at least 1°, greater misalignment was reported than when the moving object occupied five positions within that same spatio-temporal span. Thus, unlike Vreven and Verghese (2005), Eagleman and Sejnowski (2007) found that increasing the ISD increased the illusion size. Our current research also varied ISD, but over a greater number of values and compared the illusion magnitude at each of these values with the percept of motion 'smoothness'. No previous research has investigated the nature of this relationship, as there has been no systematic manipulation of either spatial and/or temporal parameters contributing to this percept of motion continuity/smoothness (Boring, 1942; Burr, Ross, & Morrone, 1986; Ekroll, Faul, & Golz, 2008; Fahle, Biester, & Morrone, 2001; Morgan & Turnbull, 1978; Tyler, 1973) in the flash-lag paradigm.

The perceptual transition from smooth to sampled motion is important for models of human motion processing. The spatial and temporal values obtained for this discrimination circumscribe the parameters of the first stage of motion processing: initial sampling by an array of oriented, spatial- and temporal frequency-tuned filters (Adelson & Bergen, 1985; Fahle et al., 2001; Watson & Ahumada, 1985). As opposed to physically continuous motion,

* Corresponding author. Fax: +61 737353388.
E-mail address: t.hine@griffith.edu.au (T.J. Hine).

0042-6989/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2009.06.010

the visibility of sampled motion is determined by whether the spatio-temporal frequency combinations of sampled motion are outside a "window of visibility" and hence the sampling goes undetected (Adelson & Bergen, 1985; Watson & Ahumada, 1985). This low-level motion processing has been identified with the 'short-range' process in apparent motion (Braddick, 1980). In the case of these short-range processes, it has been shown that the discrimination (where feedback was given) of smooth from sampled motion occurs for ISDs less than 0.3°, for stimuli and velocities ($12^\circ\ s^{-1}$) similar to that used in the current research (Fahle et al., 2001). We tested ISDs smaller and greater than this value.

However, there are 'long-range' processes beyond these short-range processes that determine the criterion of smoothness of the perceived motion (Braddick, 1974; Braddick, 1980), especially in apparent motion displays. Wertheimer's (1912/1961) original description of apparent motion noted that a unified moving percept arises from successive, discrete events given certain timings and station locations. This *optimal apparent motion* occurs when the movement generated discretely in time and space is indistinguishable from real motion (the latter is infinitely smoothly differentiable over time and space; Kolers, 1972). In this case, a single moving object is seen to traverse the entire distance between physical stimulus stations (Ekroll et al., 2008). On the other hand, a 'pure' apparent movement percept (Steinman, Pizlo, & Pizlo, 2000) occurs just when there is a percept of directional displacement between locations, for example, left-to-right or right-to-left, rather than stimuli just flashing in separate locations.

Operationalisation of apparent motion percepts has been in dispute since Wertheimer's original observations (Steinman et al., 2000). It is beyond the scope of this paper to engage in this debate, but for descriptive purposes, we note that a range of perceptual states has been recently proposed by Ekroll et al. (2008) as a result of their observations where timings were varied in apparent motion using just two stimuli separated by 2.3°. In addition to the optimal apparent motion percept described above, these researchers also describe a *part* motion percept. Stimuli are perceived at each of the stations, and they have a perception of 'jerky' motion as each moves some way towards the next station.

In the current study, we have altered the percept of motion smoothness by varying the one parameter – ISD – while keeping velocity constant. We measured the magnitude of the flash-lag illusion as a function of this parameter, and to confirm that motion smoothness was indeed altered, participants judged the smoothness of the motion percept using the optimal/part motion (smooth or jerky) dichotomy described above. As the ISD was increased, the optimal apparent motion percept was lost, and we expected the magnitude of the FLI to follow if the processes which support this percept contribute to the FLI. Indeed, the magnitude may diminish most dramatically just as the smoothness of the motion percept disintegrates. On the other hand, following Eagleman and Sejnowski (2007), there may still be a significant flash-lag effect when there is no optimum motion percept at all, rather, just part motion alone. Eagleman and Sejnowski's theory would attribute this to a motion signal associated with the part motion percept spatially biasing the location of these stimulus stations.

2. Experiment 1: FLI with optimal and 'part' motion

2.1. Methods

2.1.1. Observers

Ten observers comprising five males and five females (two authors and eight naïve participants, mean age 29.3 years) took part in the experiment. All had normal or corrected-to-normal visual acuity. Half of the naïve observers were volunteers and the other half received course credit or reimbursement for their participation. One male observer did not complete the optimal motion perception condition (see below), due to slight physical discomfort and his incomplete data set was excluded from the analysis of this condition.

2.1.2. Stimuli

Stimuli were presented on a 14 in. colour monitor with a vertical refresh rate of 72 Hz and a 640 × 480 pixel resolution. It was located 57.3 cm from the observer's eyes, where the viewing distance was kept constant with the aid of a chin rest. All stimuli were white (around $75\ cd\ m^{-2}$) displayed on a black background ($1.1\ cd\ m^{-2}$) in dim ambient lighting (around $3\ cd\ m^{-2}$ on average). All luminance measures were recorded with a Tektronix J18 1° luminance probe. Fig. 1 illustrates the stimuli used in the flash-lag condition. The flashed and 'moving' objects were right-angled triangles measuring 2.0° in both height and width, with the flashed triangle spatially inverted with respect to the moving triangle. At its nearest approach, the base of the horizontally moving triangle was located 1.5° above the centre of a white fixation cross which subtended 1.0° on each arm. The lower vertex of the flashed triangle was located 3.0° above the centre of the cross, thus creating a potential 0.5° overlap between the upper vertex of the moving triangle and the lower vertex of the flashed triangle (see Fig. 1). The motion of the moving triangle was sampled in both time (determined by 'frames' of vertical refresh of the monitor) and space (determined by location in pixels on the screen). It was, in effect, a number of discrete stimuli, each of one frame's duration (~14 ms), and presented at different successive horizontal locations on the screen only on certain frames, before re-appearing at the next location.

In all conditions, a key press by the observer initiated the trial and the 'moving' triangle appeared after a 1.5 s delay, located approximately 12° either to the left or right of the fixation cross, whereupon it was displaced horizontally across the screen at the equivalent of $12^\circ\ s^{-1}$ for two seconds. The spatial difference between the sample locations was the ISD and assumed values of 0.1° (smoothest movement), 0.4°, 0.8°, 1.6°, or 3.2°. The sampling was of just seven locations across the entire screen in the latter case (see Fig. 1). Concomitant with this discrete spatial presentation was discrete temporal presentation: the stimuli appearing in every frame, every second frame, fourth, ninth or nineteenth frame, respectively. This spatial and temporal sampling maintained a constant velocity equivalent to $12^\circ\ s^{-1}$. In the flash-lag conditions (see below), a second, inverted triangle was displayed for one frame above the moving triangle at a random location within a 2° horizontal 'window' that was adjacent to the fixation cross near the centre of the screen. The frame in which the flashed triangle appeared was always a frame in which the sampled moving triangle appeared (see Fig. 1) and was the *critical station* for the FLI comparison.

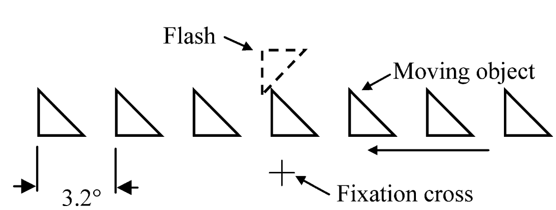

Fig. 1. Schematic of a flash-lag trial stimulus for an ISD of 3.2°. The triangular stimulus undergoing sampled motion from right-to-left (trajectory indicated by arrow) occupied the positions indicated by the solid triangles in succession for just one vertical refresh frame at a time and on every 19th frame (that is, frame number 19, 38, etc.). The flashed triangle, indicated by a broken line, always appeared within frames in which the moving stimulus also appeared. The shapes of all stimuli were mirror-reversed in left-to-right motion trials.