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Vision Research 46 (2006) 2735–2742
Vision Research
www.elsevier.com/locate/visres

Flash lag in depth

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Received 25 October 2005; received in revised form 28 December 2005

Abstract

The perceived position of a moving target at a particular point in time, indicated by a flash, is often judged to be different from its actual location. Here, we show that the position of a target moving in depth is also systematically mislocalized. We used three types of targets moving in depth at a range of speeds from 2 to 16 cm/s. (i) A target realistically rendered that included concordant looming, disparity, and perspective cues. (ii) A random dot surface whose depth was defined by disparity, without concordant perspective or looming cues. (iii) A surface of *dynamic* random dots whose depth was defined by disparity with no consistent motion visible monocularly. Subjects viewed the targets moving either towards or away from them and indicated whether the targets appeared to be nearer or farther than a continuously present reference depth at the moment that a flash was presented. A staircase procedure was used to null, and thus measure, any perceptual displacement from the reference depth. A flash lag in depth was found in which the target appeared ahead of its true position, displaced by a constant amount of time depending on the stimulus type and the direction of motion (towards or away). The time displacement varied from 76 ms (for the realistic target moving away from the observer) to 263 ms (for static random dots moving towards). These effects may depend on the confidence with which subjects were able to judge the location of our various targets: greater confidence leading to a smaller temporal displacement.

Keywords: Flash lag; Motion-in-depth; Disparity-defined form; Disparity-defined motion; Neural processing delays; Spatial localization

1. Introduction

When the instantaneous perceived position of a moving object is accessed at a particular moment, the object is reported as being ahead of its actual location (Mackay, 1958; Mertzger, 1938; Nijhawan, 1994; Sheth, Nijhawan, & Shimojo, 2000). Because a flash has traditionally been used to signal the moment in question, the phenomenon has been given the name of 'flash lag' (Nijhawan, 1994).

Recently, two studies have appeared looking at the flash lag associated with a target that moves towards or away from the observer in depth (Harris, Kopinska, & Duke, 2003; Ishii, Seekkuarachchi, Tamura, & Tang, 2004). When a target moves in depth its motion is reported by several different systems. When a target is real, or realistically rendered, its distance is defined by both disparity and perspective cues (as both of these studies used). When such a target moves towards or away from an observer it causes oppositely directed retinal motion on each retina. Each of these 2D retinal motions, if presented separately, would be vulnerable to flash lags of their own. Indeed, the magnitudes of the flash lags that these studies found (Ishii et al.: 30–100 ms, Harris et al.: 40–100 ms; classical flash lag: ~80 ms Krekelberg & Lappe, 2001) are compatible with flash lag in depth being a simple consequence of flash lags of the lateral retinal movements involved.

However, motion-in-depth can be processed by a system independent from a looming or lateral motion detecting system (Beverley & Regan, 1979; Harris, McKee, & Watamaniuk, 1997) with different timing properties (Beverley & Regan, 1979; Regan & Beverley, 1973). The disparity-based system is associated with much longer latencies for evoking eye movements (Erkelens & Regan, 1986) and has much poorer speed resolution than the non-cyclopean

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doi:10.1016/j.visres.2006.01.001

movement system (Harris & Watamaniuk, 1995), so much so that it has been suggested that there is no specialized mechanism for processing the speed of stereo-defined motion at all (Harris & Watamaniuk, 1996). Longer latencies for processing the position of a moving object might predict a smaller flash lag effect because the processed flash would not lag so far behind the slower-processed target. Also, poor speed resolution might result in an effect that did not vary as a function of speed.

To examine whether the disparity driven motion-in-depth system in isolation is susceptible to the flash lag effect, we created cyclopean motion-in-depth stimuli using dynamic random dot stereograms (DRDS). We measured 'flash lags' for targets whose motion in depth was defined by disparity alone. The size of this effect was compared to that obtained with stimuli that contained both disparity and first-order cues to motion.

2. Methods

2.1. Subjects

Eight subjects took part in these studies (seven male and one female): five using the disc stimulus and seven using the random dot stimuli (see below). All subjects had a stereoacuity of 40 s of arc or better, measured by the Titmus Randot Stereotest. Several of the subjects were paid for their participation. All experiments were approved by the York Ethics board.

2.2. Stimulus presentation

Stimuli were computer generated images presented on a Wheatstone stereoscope comprising two screens (each measuring 36 by 28 cm) viewed in an otherwise totally dark room. The equipment is illustrated in Fig. 1. Each of the screens was mounted on a railway and could be moved to viewing distances between 28.5 and 57 cm. They were not moved within an experimental session.

The angular subtense of a single pixel was approximately 4 arcmin when the screens were at a distance of 28.5 cm, and 2 arcmin at 57 cm. The images were spatially calibrated and luminance was linearized using a photometer to estimate the video gamma function. This allowed for accurate rendering of the images using anti-aliasing techniques to increase the effective resolution of our displays.

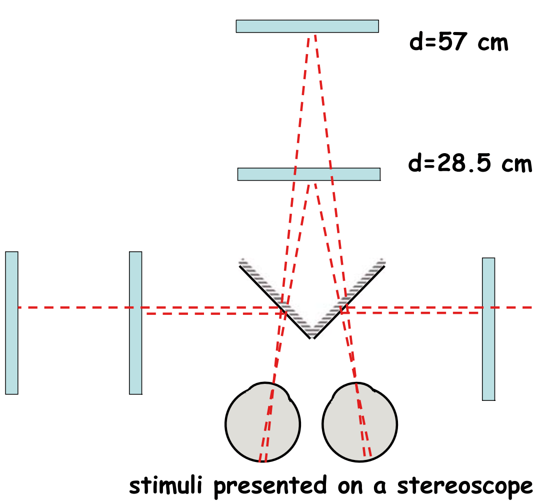


Fig. 1. Diagram of the equipment used in this experiment. Subjects viewed the stimuli on a large Wheatstone stereoscope. They sat facing two mirrors angled at 45° to displace the images of two laterally placed displays to appear on top of each other and straight ahead. The laterally placed screens could be moved on railways between distances of 28.5 and 57 cm.

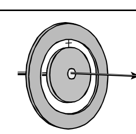
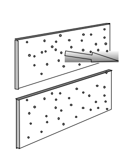
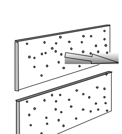
2.3. Stimuli

Three types of stimuli were used. Stimuli were devised that had combinations of disparity, looming and lateral motion that provided motion-in-depth cues. The first stimulus was a stereoscopic disc that was simulated as moving towards and away from the observer. This stimulus contained all three cues operating concordantly. The second stimulus was a sheet of random dots that contained only lateral motion and disparity cues. Lateral motion cues were present because one eye's sheet moved in one direction and the other eye's in the other direction to simulate motion in depth. The distance of the dots was kept constant thus providing a conflicting looming cue that indicated no motion in depth. The third stimulus was a dynamic random dot stimulus that contained no significant looming cues and no lateral movement but only disparity-defined motion. There was therefore no conflict between any of the three cues. The cue content of these cues is summarized in Table 1 and described in more technical detail below.

2.4. Luminance-defined stimulus (disc)

The stimulus was a luminance-defined disc that moved through the hole of an annulus (hole: 3.6° internal diameter, disc 2.8° at the moment it passed through the hole). The stimulus is shown in cartoon form at the top of Fig. 3A. The annulus was presented at the reference distance (either 28.5 or 57 cm). Linear speeds were chosen (2 and 4 cm/s at the near distance, 8 and 16 cm/s at the far distance) to produce the same angular speeds (0.47 and 0.93°/s) at both distances. Subjects judged whether the moving disc was nearer to or farther from them than this reference distance. The annulus was also used as the flash when it changed brightness for 26.7 ms to indicate the moment at which subjects were to decide where the disc was relative to the annulus. Motion of the disc in depth was determined by appropriately changing both the disparity and the size of the disc. The disparity and looming cues were always in agreement. Although to see the motion in depth required fusion of the two images, the movement of the target and its position relative to the annulus could be obtained monocularly. Therefore, as in Ishii et al.'s study (Ishii et al., 2004), the task could be done without resorting to a system that was specifically sensitive to motion in depth. The luminance-defined disc was displayed as movies with new frames presented at 75 Hz (fast movement) or 37.5 Hz (slow movement).

Table 1
The cues to motion present in the three types of stimuli used in this study

		Looming cue	Lateral motion	Disparity
Disc		Present	Present	Present
Random dot stereograms (RDS)		Conflicting with motion-in-depth cues	Present	Present
Dynamic random dot stereograms (DRDS)		x	x	Present

The monitor image-refresh rate was 75 Hz. The flash duration was 26.7 ms (two image-refresh times).

2.5. Random dot stereogram stimulus

This stimulus comprised two frontoparallel random dot surfaces (each 30° wide by 6° high) with a horizontal gap of 0.7° between them, in the centre of which a small fixation cross was drawn. The stimulus is illustrated in cartoon form above Fig. 3C. Each dot had a diameter of 8 arcmin. When the left and right eyes' images were fused, the top and bottom surfaces appeared at different distances. The top surface moved in depth relative to the fixed-position lower surface. The moment at which the position of the top surface was to be judged relative to the bottom surface was indicated by all the dots in the bottom surface changing luminance for 30 ms. Subjects indicated whether the moving surface was closer to or farther from them than the lower surface at the moment of the flash. For this stimulus, the motion of the dots (to the left or right in opposite directions in the two eyes) was available to either eye viewing monocularly. However, the position of the top surface relative to the bottom surface at any time could only be extracted from the fused image. Therefore, although the motion in each eye was visible and potentially vulnerable to a flash lag effect, the task could not be performed except by access to a system able to extract position-in-depth information from a disparity-defined object. The dots were present throughout the trial and did not change in size or configuration as they moved towards or away from the observer: the looming cue thus continually indicated no motion in depth. Appropriately, there were no vertical displacements of any dots in the display. The random dot stereogram stimulus (RDS) stimulus was displayed as movies with new frames presented at 33.3 Hz. The monitor image-refresh rate was 100 Hz. The flash duration was 30 ms (three image-refresh times).

2.6. Dynamic random dot stereogram stimulus

For this stimulus, the overall arrangement was the same as the random dot stereogram stimulus (see cartoon above Fig. 3B) except that the dot pattern on each surface was randomly regenerated between frames in the movie. Each individual dot had a lifetime of a single movie-frame (30 ms) during which its three-dimensional position relative to fixation was defined by its disparity with its counterpart in the other eye. During each dot's limited lifetime it did not move. Thus the movement of the top surface relative to the lower surface could only be deduced from its progress through a series of positions, each one of which had a different depth from the one before. There was thus no velocity or position information available in either eye's image alone. The task could only be performed using cyclopean depth information. The moment for judgement was indicated as for the RDS by all the dots in the lower surface changing luminance for 30 ms at which point subjects indicated whether the target (the upper sheet) was closer to or farther away from them than the lower reference plane. The size of the dots in the DRDS stimuli, just as for the RDS stimuli, was not adjusted according to distance so, for both these stimuli, the looming cue indicated no motion in depth. However, the DRDS stimuli provided a weaker absence-of-looming cue then the RDS stimuli since the absence of coherent monocular motion limits the effectiveness of dynamic monocular depth cues (Allison & Howard, 2000b). For our DRDS stimuli, the time interval during which looming could be computed for individual points was limited to just 30 ms, as opposed to around 0.5 to 1.5 s for the RDS stimuli. The DRDS stimulus was displayed as movies with new frames presented at 33.3 Hz. The monitor image-refresh rate was 100 Hz. The flash duration was 30 ms (three image-refresh times).

2.7. Experimental procedure

The experimental procedure was the same for all stimuli. Subjects viewed a target that started from a position either farther away from or closer to the observer than a reference. Only one stimulus type was presented in each 20-min session. Within each session trials contained stimuli with different target velocities and directions of motion which could be either towards or away from the subject. Trials were presented in random order. The velocities and starting positions used for each of the three stimulus types are given in Table 2. The target moved towards and past the reference at a speed that was fixed in cm/s. At some point along the target's journey, a flash was presented (see stimulus descriptions above) and subjects indicated by a two-alternative forced choice whether the target was closer to them or more distant from them than the reference at that moment. The timing of the flash event was adjusted relative to the movement of the target until the moving target was seen neither in front of nor behind the reference position using a staircase procedure i.e., the flash lag was nulled. The large step in the staircase corresponded to two movie images, and small step corresponded to one movie image. The step was changed from large to small after four reversals but was presented for a fixed number of trials, enough to include around 10 reversals with the smaller step size. The procedure is shown diagrammatically in Fig. 2.

2.8. Data analysis

Data obtained in terms of movie frames were converted to a position in cm from the reference location. Our convention is that +ve means closer to the viewer. A displacement backwards along the trajectory of the target corresponds to the stimulus being judged as being ahead of its actual location. The position of the stimulus actually perceived as aligned with the reference distance was obtained for each stimulus condition as the average position of the stimulus corresponding to the

Table 2
The stimulus parameters used in these experiments

Stimulus	Condition			Viewing (reference) distance (cm)	Start distance (cm)	Speed (cm/s)	Speed (degree of disparity/s)[a]
Disc	Near	Slow	Away	28.5	26.5	2	0.88
	Near	Slow	Towards	28.5	30.5	−2	−0.88
	Near	Fast	Away	28.5	26.5	4	1.76
	Near	Fast	Towards	28.5	30.5	−4	−1.76
	Far	Slow	Away	57	65	8	0.88
	Far	Slow	Towards	57	49	−8	−0.88
	Far	Fast	Away	57	65	16	1.76
	Far	Fast	Towards	57	49	−16	−1.76
RDS & DRDS	Far	Slow	Away	57	53	5.23	0.58
	Far	Slow	Towards	57	61	−5.23	−0.58
	Far	Fast	Away	57	53	8.08	0.89
	Far	Fast	Towards	57	61	−8.08	−0.89

Negative velocities refer to movement towards the subject.
[a] Speeds were constant in linear terms (cm/s) and therefore did not have a constant rate of change of disparity. These numbers are approximate averages.

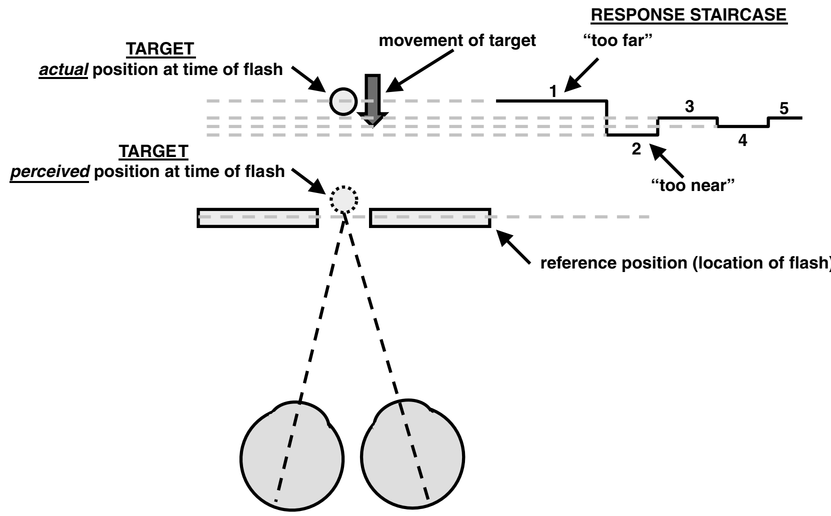


Fig. 2. Diagram of the procedure used in this experiment. A target moved either away from or towards the subject and the subject indicated whether the target was closer or farther than the reference distance at the time of a flash. Here, motion towards the subject is illustrated using the annulus of the luminance-defined stimulus. The principle is the same for all three stimulus types. In the response to the subject's decision, the position of the stimulus at the time of the flash was varied in a staircase fashion until subjects reported 'closer' and 'farther' equally often.

movie frames of the small step reversals, averaged for each subject and condition and for three or four repetitions. The standard deviations of these estimates were squared to provide an estimate of the variances of each stimulus position. These positions and variances were expressed as times.

3. Results

3.1. Flash lag magnitude

The staircase procedure indicated the movie frame at which the stimulus appeared to be aligned with the reference distance as it moved directly towards or away from the subject. The time by which this differs from the frame in which they were actually accurately aligned was calculated from the number of frames difference and the duration of a single frame. Positive numbers correspond to this point being closer to the subject. Thus a positive number when the stimulus is moving away from the observer, or a negative number when the stimulus is moving towards, corresponds to a displacement backwards along the target's trajectory being required to null the flash lag effect. These displacement times were all in the conventional direction i.e., the moving stimulus was reported ahead of its actual location at the time of the flash in all conditions (Fig. 3).

The mean temporal displacement from the reference distance for each condition is plotted as a function of the metric speed in Fig. 4. This graph indicates that the magnitude of the flash lag in time did not depend on stimulus speed over the range used and was independent of viewing distance for the ring stimulus since the 2 and 4 cm/s data points were obtained at one distance and the 8 and 16 cm/s at another (corresponding to angular speeds of 0.47 and 0.93°/s at both viewing distances). We therefore pooled data from all stimulus speeds and distances to produce six data points (towards and away for each stimulus: Fig. 5).

A repeated measured ANOVA was conducted only for subjects who participated in all the conditions. All flash lags were significant (RDS: $t(6) = 4.90$, $p < .01$; DRDS: $t(6) = 4.79$, $p < .01$; disc: $t(4) = 3.33$, $p < .05$). There was a significant difference between the conditions ($F(2,9) = 5.00$, $p < .05$). There was a significant asymmetry ($F(1,7) = 6.35$, $p < .05$) with away motion being associated with smaller flash lags than towards motion.

3.2. Variances

Fig. 6A gives the variances for each subject in each condition and the mean value. Fig. 6B plots each variance against the size of the corresponding flash lag effect. There was a correlation between the variance and the size of the flash lag for both away movement (slope = 0.04 ms^{-1}, $r^2 = 0.43$) and towards movement (slope = 0.025 ms^{-1}, $r^2 = 0.23$). The variances were not significantly different between the three conditions.

4. Discussion

These experiments have shown that a flash lag effect occurs for objects moving in depth. This effect goes beyond previous reports using luminance-defined motion (Harris et al., 2003; Ishii et al., 2004) in which the magnitude of the effect was comparable to that expected from the flash lag effect in each eye alone (about 70–150 ms). Substantially larger flash lags where found when motion in depth was simulated using RDS compared with DRDS, the difference

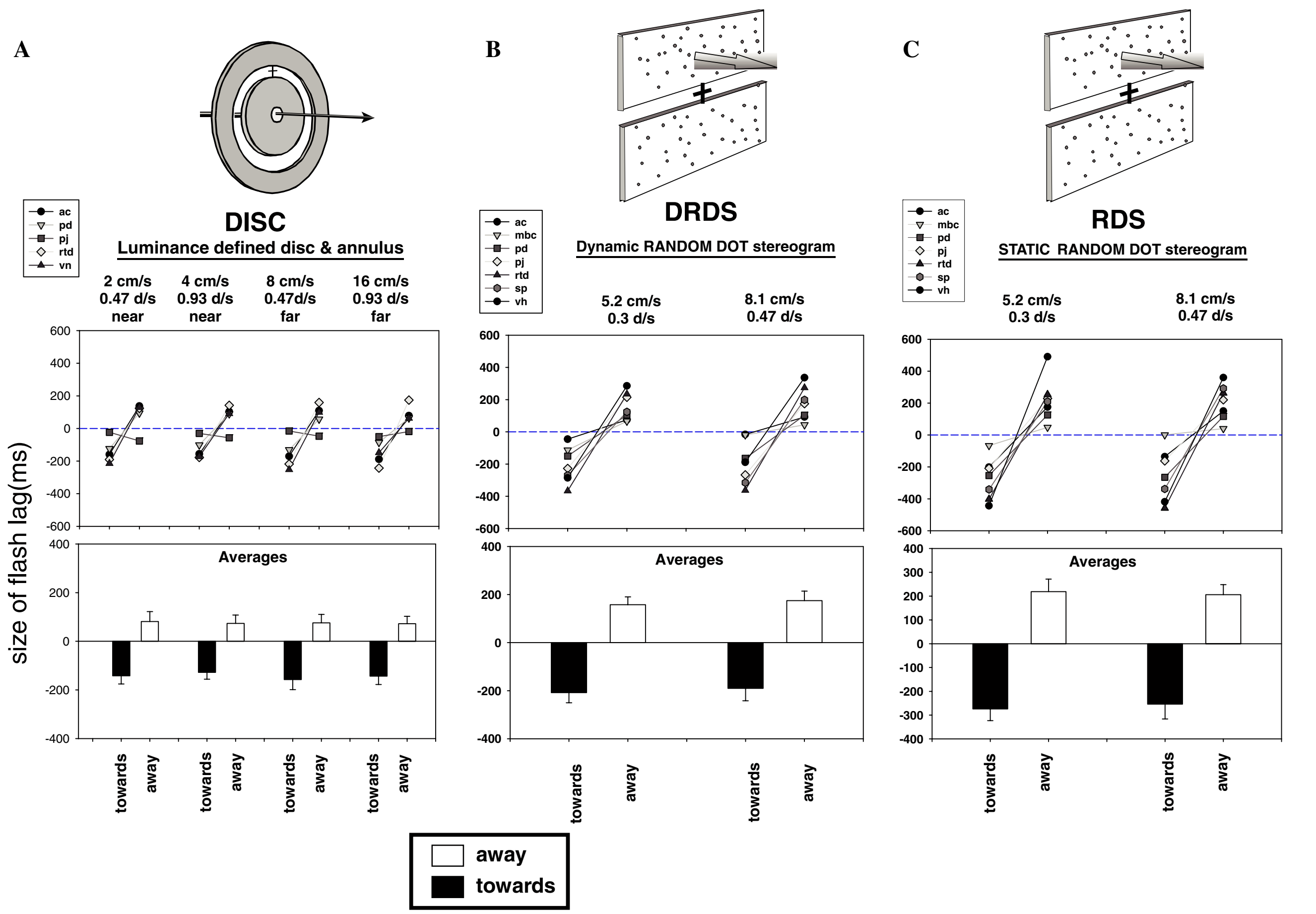


Fig. 3. The three stimuli used in this study and the size of the flash lags they evoked. (A) The luminance-defined figure consisted of a static ring through which the target circle passed with a fixation cross in between. The ring flashed to indicate the moment to assess the position of the target. (B) The disparity-defined stimulus consisted of two sheets of dots divided by a horizontal gap of 0.7°. A fixation cross was positioned in the middle of this dividing gap. The top sheet moved in depth relative to the bottom sheet. The moment at which the judgement was to be made was indicated by all the dots in the display increasing their luminance for one frame. (C) The dynamic disparity-defined stimulus had the same spatial structure as the disparity-defined stimulus but each dot was only on for a short lifetime during which it did not move. The movement of the target sheet thus had to be deduced from a series of positions obtained from a sequence of instantaneous, disparity-defined positions. Below each of the stimuli are the times by which each stimulus was perceived ahead of its actual position for each subjects. A positive value indicates an away shift, a −ve value towards. The lower panel shows the times averaged across subjects with standard errors.

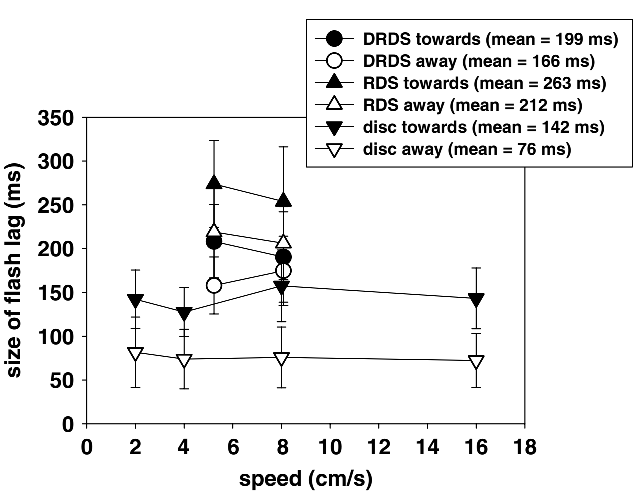


Fig. 4. The average size of the flash lag effect (in ms) for each stimulus and each direction of motion as indicated on the key, plotted (with standard error bars) as a function of speed of motion in depth. There was no effect of stimulus speed on the size of the effect for any of the stimuli tested.

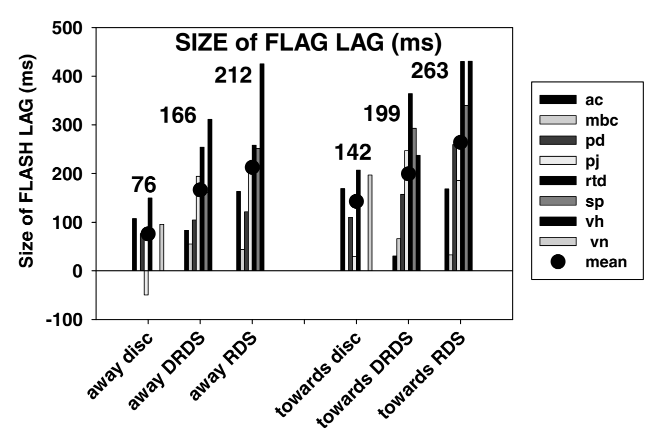


Fig. 5. Summary of sizes of all the flash lags measured in this study for each subject. The mean values are plotted as circles and the numbers are given by each histogram.

reaching over 400 ms in some subjects. Interpreting this increased size could reveal valuable clues to interpreting the flash lag phenomenon in general.

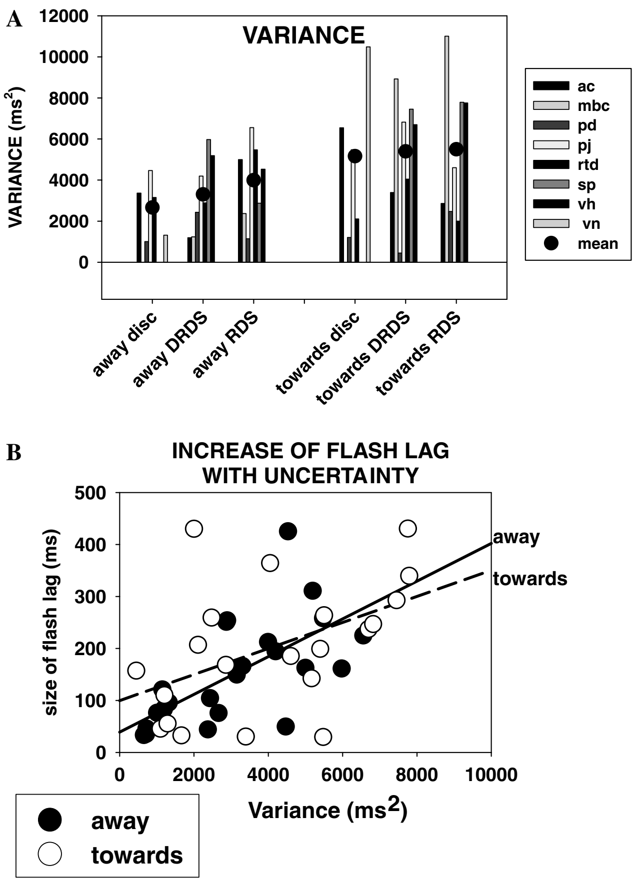


Fig. 6. (A) The magnitude of the variance for each subject is plotted as a histogram for each condition. The average value for each condition is shown as a black circle. (B) The size of the flash lag was correlated with the variance of each condition (away, solid line, slope = 0.04 ms^{-1}, $r^2 = 0.43$; towards, dashed line, slope = 0.025 ms^{-1}, $r^2 = 0.23$).

4.1. The differential latency model

The mechanism for flash lag has been the subject of intense debate. The explanation based on a longer processing time for static versus moving objects proposed by Sheth et al. when they renewed interest in the flash lag effect (Ogmen, Patel, Bedell, & Camuz, 2004; Sheth et al., 2000; Whitney & Murakami, 1998; Whitney, Murakami, & Cavanagh, 2000) no longer appears tenable (Arrighi, Alais, & Burr, 2005; Eagleman & Sejnowski, 2000; Krekelberg & Lappe, 2001). In this model, flash lags are the result of a longer processing latency for flashed versus moving objects. For the flash lag effect to be interpreted as a flash being processed more slowly than the position of the moving target then an increase in flash lag magnitude indicates either that the flash is processed more slowly than usual or that the moving object is processed more quickly. Neither of these seems intuitively likely given the large increase (up to 400 ms) found between the DRDS and RDS conditions, and neither are compatible with motion-in-depth being processed more slowly than lateral motion (Erkelens & Regan, 1986).

The longer flash lags found for movement that required disparity processing may be thought to arise from a two-step process. First a conventional flash lag in measuring 2D position, and then this 2D position is input to the motion-in-depth system, which then has its own additional lag. These types of motion detection are independent (Beverley & Regan, 1979; Portfors & Regan, 1997). This model is consistent with the RDS lags being longer than the DRDS lags, but we obtain the apparently contradictory result that the ring-and-disc lags are much shorter. Delaying the movement of the target more (by passing it through two stages which each adds a delay) should bring it closer and closer to the originally longer-delayed flash. That is, a system with multiple stages (RDS and DRDS) should have a smaller flash lag than a system with fewer stages (ring). But we find that it has a longer flash lag. The results of any studies investigating motion-in-depth when non-disparity cues are available (e.g., Ishii et al., 2004) are probably dominated by these monocularly available cues.

4.2. The postdiction model

An alternative explanation has been suggested, termed ‘postdiction’ (Eagleman & Sejnowski, 2000). In postdiction, literally “saying after the event”, the reason for flash lag occurring is not because of different processing delays but because of differences in the size of temporal integration windows for judging the position of different stimuli. This account supposes that the window of time within which the position of the moving stimulus is judged, is longer than that for the flashed stimulus. Hence, relative position judgements are made based on information gathered somewhat after the flash event. The size of an object’s time window is postulated to be related to its salience, i.e., higher salience objects are judged within smaller time windows (Eagleman & Sejnowski, 2000) so flashing and moving stimuli of the same salience would produce no flash lag.

Applying this argument to the present data suggests that the ring and disc of our stimulus (see Fig. 3A) have more closely corresponding saliences than the flashed and moving sheets in the RDS and DRDS conditions. In support of this suggestion, flash lag magnitude did vary in proportion to its variance, corresponding to a measure of easiness-of-task and therefore perhaps salience.

4.3. Temporal sampling of the scene

An explanation of the flash lag phenomenon related to postdiction is provided by Brenner and Smeets (2000). Their idea is that the flash lag is a result of the time taken to sample the position of the moving target in response to the flash. They suppose that we don’t have access to a ‘snapshot’ of the scene at the time of the flash. By providing information that allowed subjects to anticipate the flash, thus speeding up the time to initiate sampling, they found that the flash lag was much reduced. This would not be expected from a simple postdiction model. Under this temporal sampling hypothesis, the time taken to initiate sampling of the surface's position in our RDS condition would need to be significantly longer than that in the DRDS condition. It is not obvious why measurement of the target's position following the flash should be triggered at different times for the different stimuli, although the possibility is consistent with some of the threshold data on motion in depth. For example, Cumming and Parker (1994) show data where RDS thresholds were poorer than for DRDS. It is also well known that motion in depth thresholds can be much poorer than those for their monocular counterparts (e.g., Tyler, 1971; Sumnall & Harris, 2002). Although temporal sampling can influence the flash lag effect, it cannot be a full account.

4.4. Flash lag and positional uncertainty

All of our results are consistent with the prediction of shorter lags when more reliable information is available about an object's position. Several studies have proposed accounts of the flash lag effect in which the lag is related to the reliability of position estimation (e.g., Baldo, Kihara, Namba, & Klein, 2002; Baldo & Namba, 2002; Eagleman & Sejnowski, 2000; Kanai, Sheth, & Shimojo, 2004). Kanai et al. (2004) reduced the reliability of position estimates by using peripheral stimuli and found increased lags in comparison to those for central stimuli. Fu, Shen, and Dan (2001) reduced reliability of position estimation by blurring the edges of the target and obtained a flash lag effect not found when unblurred targets were used.

We suggest that the differences in flash lag magnitude between our disc, RDS, and DRDS conditions can similarly be related to the reliability of the percept of target depth. Differences in the reliability of the target depth percept could arise as a consequence of the depth-cue combination process. In our displays, both disparity and monocular size/texture cues (and their temporal derivatives) were available and contributed to the perception of depth of the moving targets. However, our stimuli differed in the extent to which monocular cues agreed with disparity. In the disc stimuli, monocular cues agreed with disparity. In the RDS stimuli, monocular cues conflicted with disparity as they signalled that the target's depth was fixed at the same distance as the reference (45 cm) during the target motion. In the DRDS stimuli, monocular cues were in conflict with disparity but the conflict was substantially weaker than in the RDS stimuli. This is because the conflicting looming cues which signal that the RDS stimuli are not moving in depth are unavailable (or at least very much weaker) in the DRDS stimuli. Thus, there is less disagreement between cues in the DRDS stimuli. Allison and Howard (2000b) provided evidence in support of this, showing that perception of changing slant from disparity is less influenced by conflicting texture cues in DRDS displays than in RDS displays.

In a cue combination process, individual cue reliabilities are estimated dynamically and used to determine relative weights to attach to each cue (e.g., Ernst & Banks, 2002; Landy, Maloney, Johnston, & Young, 1995). A weakness in this Bayesian approach has always been determining how the brain estimates the reliability of each cue. Individual cue reliability may be determined in part by the degree of correlation with other available cues, so that more discrepant cues are considered less reliable (e.g., Fine & Jacobs, 1999). The total reliability of the combined cue estimate is therefore lessened for stimuli in which the component stimuli disagree (Goodale, Ellard, & Booth, 1990). Thus in the present case, the certainty of an object's position estimate should be lower for cue-conflict stimuli than for cue-consistent stimuli. Our RDS stimuli had greater depth cue-conflict than our DRDS stimuli (see e.g., Allison & Howard, 2000a) and produced greater lags. Observers' settings varied with variance (Fig. 6B), compatible with the suggestion that the lag increases with the uncertainty of the target's position. Our ring and disc stimuli had the most consistent depth cues and exhibited the smallest lags. Thus, we suggest that positional uncertainty is an important aspect of the flash lag effect we see here.

Kanai et al. (2004) suggest that position estimates for a moving target have a relatively broad probability distribution: excitation of cells ahead of the target's path and inhibition behind it, tend to bias the estimate forward. When the probability distribution is narrower, the lateral connections exert relatively little effect. In addition, they suggest that the time period over which the position of the target is monitored is longer when target position has greater uncertainty to maintain consistent level of certainty. This principle predicts longer flash lags for targets with greater positional uncertainty both for movement in 2D and for movement in depth.

4.5. Comparison of motion towards and away

Motion of a stimulus towards an observer showed a larger flash lag (and larger variance) than motion away. Why might this be? Looming cues increase non-linearly as objects approach. Therefore if natural looming cues are missing, this will cause a larger cue conflict for motion towards an observer. Larger cue conflict could give rise to greater positional uncertainty and thus greater lags, as explained in the previous section. The asymmetry exhibited by the luminance-defined disc may be related to the properties of different neuronal sets being responsible for motion towards and away (expansion and contraction) (Tanaka, Fukada, & Saito, 1989; Tanaka & Saito, 1989). Motion away from the fovea (as seen in a target looming as it approaches) is associated with larger variances (Kanai et al., 2004) and lower sensitivity (Edwards & Badcock, 1993) consistent with our association of larger variance with a larger effect.

5. Conclusions

This paper is the first demonstration of a cyclopean flash lag effect. The effect is surprisingly large which takes it outside the range conceivably compatible with a differential latency hypothesis. The effect is compatible with a position-determining mechanism that is affected by the reliability of positional information.

Acknowledgments

Laurence Harris was sponsored by the Natural Sciences and Engineering Research Council of Canada (NSERC). Phil Duke was sponsored by an NSERC grant to Ian Howard.

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