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Motion extrapolation is not responsible for the flash–lag effect

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Abstract

To achieve perceptual alignment between a flashed target and a moving one, subjects typically require the flashed target to be aligned with a position that the moving target will only reach some time after the flash (the flash–lag effect). We examined how the magnitude of this misalignment changes near an abrupt change in velocity. The magnitude of the misalignment turns out to depend on the target's velocity *after*, rather than *before*, the flash. Thus, the misalignment cannot be caused by motion extrapolation. Neither can it be the inevitable consequence of a difference between the time it takes to process flashed and moving stimuli, because the magnitude of the misalignment is influenced by the extent to which subjects can anticipate the flash. We propose that it is the consequence of having to 'sample' the moving target's position in response to the flash. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Most human subjects can easily pick up a static object as they walk past it. Considering the time that it takes for visual information to reach the brain and be transformed into commands for the muscles, and the time that it takes for such commands to reach the muscles and generate a response, this ability cannot be considered self-evident. For the hand these delays amount to at least 100 ms (Prablanc & Martin, 1992; Brenner & Smeets, 1997). At a normal walking speed one will move about 10 cm during this time. Thus if visuo-motor delays are not accounted for, one will grasp at least 10 cm from the object. Perceiving the object at a position that is an extrapolation from its actual position in the direction of its motion (relative to oneself) could help compensate for such delays.

Systematic misjudgement of the relative positions of flashed and moving targets has recently been interpreted as evidence for such extrapolation (Nijhawan, 1994, 1997). Surprisingly, however, the relationship between the positions of flashed and moving targets was not misjudged when subjects tracked the moving target with their eyes (Nijhawan, 1997). It is conceivable that only the motion on the retina is extrapolated (Berry, Brivanlou, Jordan & Meister, 1999). However, if so it is unlikely that the findings have anything to do with the way we circumvent visuo-motor delays in our actions, because if an object that we are interested in is moving, we tend to pursue it with our eyes, so that there is little retinal motion.

An alternative explanation for the above-mentioned misjudgements is that for some reason the visual delays are different for flashed and continuously visible targets, and that we do not take account of this difference (Whitney & Murakami, 1998). In accordance with this idea, it has been shown that the magnitude of the misalignment can be influenced by manipulating the detectability of the targets (Lappe & Krekelberg, 1998; Purushothaman, Patel, Bedell & Ogmen, 1998). However, Nijhawan has shown that even a very bright flash can be perceived to lag behind a dim moving target (demonstration during the European Conference on Visual Perception in Trieste on the 24 August 1999).

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Why should flashed targets be processed so much more slowly?

Perhaps there is some kind of facilitation along the moving target's trajectory (Berry et al., 1999; Krekelberg & Lappe, 1999), but if so it is not clear why the misalignment should also be found when the flashed and moving targets coincide spatially but have different colours (Nijhawan, 1997). Perhaps position signals are averaged over long periods of time, and the last visible position continues to contribute to this average if the target disappears (Lappe & Krekelberg, 1998; Krekelberg & Lappe, 1999), but if so, there must be some mechanism to ensure that retinal position signals are not averaged for 500 ms across saccades.

We propose an alternative explanation. Since the moving target's image shifts across the retina, the spatial alignment task involves ascertaining the moving target's position at the moment of the flash. It is usually implicitly assumed that parallel processing within the visual system enables relative positions to be judged from a kind of 'snapshot' at the time of the flash. However, the visual system may not have access to such a 'snapshot'. In that case it would have to select a moment to 'sample' the moving target's position. Choosing an incorrect moment will obviously result in a spatial error. Since the moment can only be determined after the flash, any time it takes to initiate the sampling process will result in the sampled position corresponding to a later moment than the time of the flash. Our proposal is that the misalignment between flashed and moving targets is caused by not accounting for the time it takes to sample the moving target's position in response to the flash.

In the present study we confirm Whitney and Murakami's (1998) evidence that the misalignment cannot be due to motion extrapolation by examining the magnitude of the misalignment between a moving and a flashed target near a change in the moving target's velocity. We also present support for our 'sampling' hypothesis by showing that helping subjects anticipate the moment of the flash can reduce the misalignment considerably.

2. Materials and methods

Stimuli were presented at 120 Hz on a high-resolution computer screen at a distance of 3.2 m in an almost dark room. Two 6-mm dots, 6 cm apart, rotated around a central stationary dot that the observer fixated throughout the experiment. On each presentation the two dots first rotated at either 120 or 240°/s for a randomly chosen period of time (1–2 s), and then at the other value for another 500 ms (see Fig. 1). At some moment a 40×2 mm bar was flashed for one frame across the fixation dot (see inset in Fig. 1).

The subject could manipulate the orientation that the bar would have on subsequent presentations with the computer mouse. Each trial consisted of as many presentations as the subject needed to make his setting. His task was to manipulate the bar's orientation so that it was aligned with the three dots at the moment it flashed. He indicated that he was content with his setting by pressing a button. We measured the set angle between the flashed bar and a line connecting the three dots at the moment of the flash (*orientation error*).

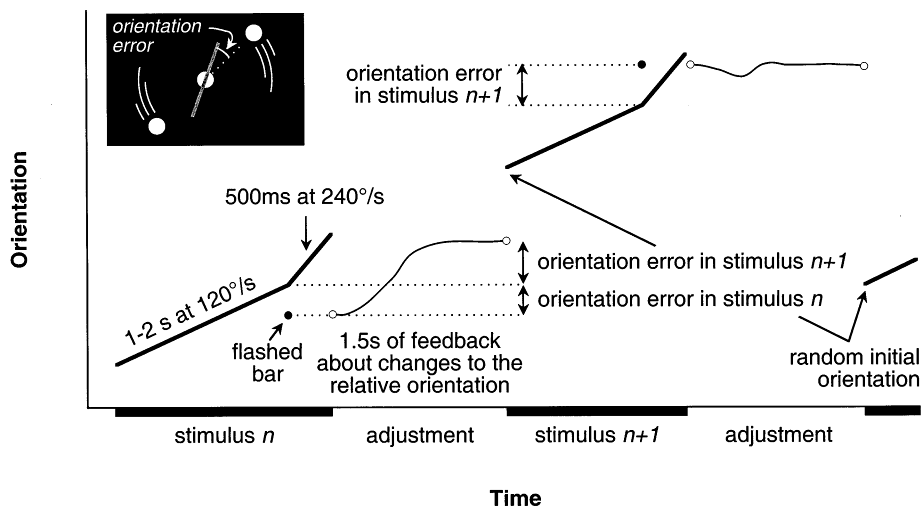

Fig. 1. Schematic representation of part of a trial during which the flash coincided with an increase in velocity. Two presentations of the moving dots (thick lines) and flashed bar (solid circles) are shown (stimulus n and stimulus $n+1$), each followed by an interval during which the bar was constantly visible and the subject adjusted its orientation. The thin line connecting the open circles shows the orientation of the bar during the interval between stimulus presentations. Its initial orientation was the same as it had been when flashed during the preceding presentation. Changing its orientation during the adjustment interval determined the flashed bar's orientation (relative to the dots) during the next presentation.

The *orientation error* was determined for various values of the time between the moment the bar was flashed and the moment the velocity changed. The flash could occur between 150 ms before and 150 ms after the change in velocity, in steps of 25 ms. Trials with different values were presented in random order. Increases and decreases in velocity were studied in separate sessions. Obviously the timing of the flash relative to the change in velocity was the same for all presentations within a trial. However, the dots could have any orientation when the bar was flashed. What subjects manipulated by moving the computer mouse was the next flashed bar's orientation with respect to the dots (i.e. the orientation error).

The bar was only visible for one frame on each presentation, and at a different orientation on every presentation. To help subjects establish the relationship between bar orientation and movement of the mouse we provided them with feedback about the extent to which they were changing the bar's orientation. During the 1.5 s between stimulus presentations a bar appeared. Its initial orientation was the same as when it had flashed, but it turned when the computer mouse was moved. The timing of the experiment was such that most adjustments were made during the interval between presentations.

Irrespective of whether subjects extrapolate the dots' motion or combine the orientation of the flashed line with the dots' positions some time later, the orientation error is expected to be twice as large if the dots move twice as fast. However, if the error is introduced by extrapolation this is because of the difference in velocity *before* the flash, whereas if it is introduced by determining the dots' position too late it is because of the difference in velocity *after* the flash. Near a change in the dots' velocity the predictions therefore differ. We used this difference to determine the error's origin.

In a third session, the orientation at which the bar would flash was faintly visible from the beginning of each stimulus presentation (i.e. as soon as the moving dots appeared). The flash always occurred together with an increase in velocity. In this case subjects still had to judge the orientation of the moving dots at the moment the line flashed. There is no reason to expect the dim bar to influence the perceived positions of the moving dots. Neither is it likely that the flash will be detected much faster just because one knows its orientation in advance. The dim bar itself does not provide information about when the target will flash. Once the subject has started aligning the flash with the dots, the dim bar does provide an indication of when the subject will *perceive* the flash, because aligning the flash with the dots obviously implies that the flash will appear to occur when the dots appear to cross the dim bar. However, for the spatial aligning task this can only improve performance if knowing that the target is about to flash reduces the time that it takes to detect the flash. Thus, if a difference between the time that it takes to process flashed and moving stimuli is responsible for the misalignment, the dim bar should make no difference.

However, the dim bar provides the possibility to perform the task quite differently: as a temporal rather than a spatial alignment task. Subjects can compare the time of the flash with the time the dots pass the dim bar. If the misalignment is caused by it taking longer to process a flashed stimulus than a moving one, then performing the task in this manner will make no difference. However, if the misalignment is caused by the time that it takes to sample a moving target's position in response to a flash, then making use of this new possibility should eliminate the misalignment, because the necessity to sample the moving target's position is circumvented (one judges the moment it passes the bar instead).

3. Results

As was to be expected, our subjects made systematic, velocity-dependent errors in the set orientation of the flashed bar (open symbols in Fig. 2). A set angle of 0° would indicate that they had managed to align the flashed bar with the dots. A positive value indicates that the bar was ahead of the dots when perceptually aligned. The difference between the orientation error 150 ms before and after the change appears not quite to reach the predicted factor of two for all subjects, but it is quite close in most.

The lines in the figure show the orientation error that would arise from aligning the bar with the dots' orientation 60 ms after the flash. Our data suggest that the dots' orientation was indeed determined about that much later.

When the bar was dimly visible throughout the presentation (at the orientation at which it flashed), the authors managed to align the bar with the dots. The naive subjects still made systematic errors, but their errors were less than half of what they were before (solid symbols in Fig. 2).

4. Discussion

Our results show that motion extrapolation is not responsible for the flash–lag effect. If subjects had extrapolated the dots' motion, the new velocity would only have influenced the set orientation (i.e. the points would only have had the 'high' value in A and the 'low' value in B) when the bar was flashed well after the change in velocity had taken place. In fact, the settings were even influenced by the new velocity when the bar

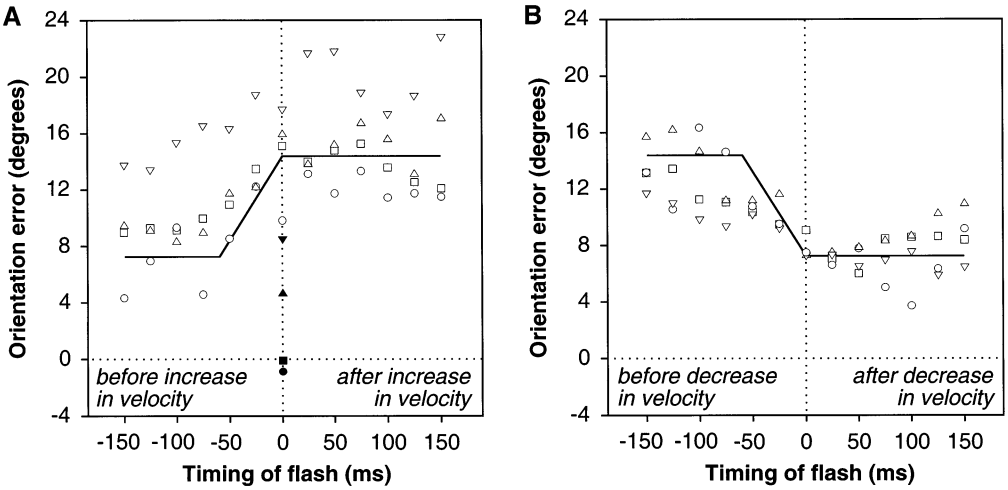

Fig. 2. How the orientation error depends on the relative timing of the flash and the change in velocity. The symbols show average settings by the two authors and four naive subjects. The authors (circles and squares) made settings for both increases (A; 120–240°/s) and decreases (B; 240–120°/s) in velocity. Each naive subject (triangles) made settings for one of the two. Each subject set the orientation of the bar ten times for each value of the time the velocity changed. Performance when the bar was dimly visible throughout the presentation is depicted by solid symbols (averages of 20 settings). Twenty-one of the 1120 settings were discarded as errors (set angle smaller than −20° or larger than 40°). The thick lines show the errors subjects would make if they aligned the flashed bar with the moving target's orientation 60 ms after the flash. Note that although the change in velocity was abrupt, the amount by which the moving target will turn during the 60 ms after the flash shifts gradually between trials in which the flash occurred 60 ms before the abrupt change in velocity, and ones in which they occurred simultaneously.

was flashed before the change took place. When the flash occurred simultaneously with the change in velocity, the orientation error was similar to the error found when the flash occurred 150 ms after the change. Motion extrapolation would predict it to be the same as the error found when the flash occurred 150 ms before the change, because the preceding target velocity is the same in both cases, so the extrapolation should be the same.

Thus, the orientation of the dots appears to be determined about 60 ms after the flash. This could be due to a difference in neural delays, whereby flashed stimuli take 60 ms longer to process than moving ones (under the conditions of the present study). If so, the neural responses signalling the flash arrive in the brain at the same time as neural responses about the moving target's position 60 ms later. However, we also found that if subjects can anticipate the orientation of the flash, the timing error decreases considerably. A more likely explanation is therefore that the flash–lag effect arises because of the time it takes to 'sample' the moving target's position in response to the flash.

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