Perceived Instantaneous Position of Moving Objects: Experiments and Mechanisms.

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Abstract

Latencies in cortical processing lead to discrepancies between the information available to cortex and the actual state of the environment. To survive in a rapidly changing environment an animal as well as an artificial robot has to correct its *actions* to account for such information processing latencies. Recently, it has been proposed that such a latency-correction also takes place in *perception* [6]. We show that this hypothetical latency-correction mechanism decreases the amount of correction when less information about the stimulus is present. Moreover, we show that the correction can only be correct for a single latency even though the latencies in the visual system are highly variable. These properties are peculiar for a latency-correction mechanism and we suggest an alternative interpretation based on differential latencies in the visual system.

1 Background

Moving objects can travel a considerable distance during the time it takes a neural signal to travel from the retina through the visual cortical areas and on to the motor centres. The fact that we are still able to play a game like squash shows that, somewhere along the pathway between retina and motor action, this delay is taken into account. Recently, however, it has been suggested that a similar latency-correction operates in the early stages of perception. If this is indeed the case, such a mechanism could also be useful for the survival of robots in a real-time environment. With this in mind, we pursue this hypothesis to determine whether humans actually make use of such a mechanism.

Nijhawan [6] showed that stroboscopically illuminated moving objects appear to lag behind objects that are continuously illuminated (See figure 1). He interpreted this as

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a difference in *predictability* of the two objects. The briefly flashed objects, being "unpredictable", are seen at the position they actually were when their light hit the retina. Continuously lit objects on the other hand are "predictable" and their perceived position can therefore be predicted forward to correct for the latency the neural signal must have incurred while travelling to the cortex. In this paper we start from the hypothesis that this flash-lag visual illusion is caused by a latency-correction mechanism and investigate its properties.

First we will look at what makes a stimulus predictable; from a computational viewpoint we are interested in the time the mechanism needs to observe a stimulus in order to estimate its speed and thereby its future path. In our experimental setup the temporal aspects of the stimuli are controlled by two parameters. First the frequency with which the flashed objects are shown and secondly the duration of a single flash. The influence of these two parameters on the flash-lag effect is investigated in sections 3.1 and 3.2. The surprising finding is that no dichotomy could be discerned: the hypothetical mechanism does not divide stimuli with different frequencies or durations into the classes 'predictable' and 'unpredictable'. Instead, all seem to be equally predictable, but the amount by which the stimuli are predicted along their expected future path varies.

Secondly we will determine how well the latency-correction mechanism corrects for changes in the latencies. This is tested by varying the luminance (and hence the latency) of the stimuli. Here we find that the changing latencies are not taken into account by the (hypothetical) latency-correction mechanism.

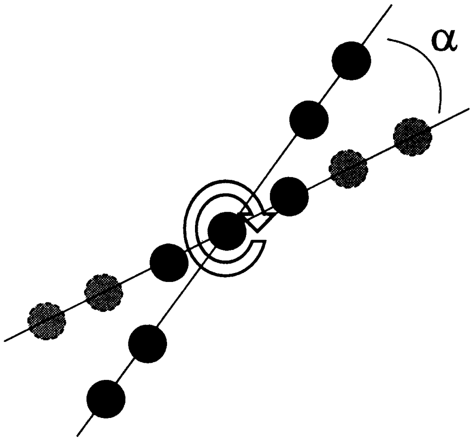

Figure 1: The flash-lag illusion. Seven dots rotate rigidly around a common centre. The three inner dots are shown continuously, while the outer dots are repetitively flashed for brief periods of time. Subjects report that the outer dots appear to lag behind the three inner dots. The gray dots show the position at which the outer dots are "flashed", the black dots show the percept. The angle α is called the lag-angle. The arrow denotes the rotation direction.

Finally, in the discussion, we propose a different way of looking at the flash-lag visual illusion. This proposal involves no prediction mechanism, but uses known spatio-temporal interactions between stimuli as the basis for an explanation of the lag-effect.

2 Materials and methods

The stimulus (figure 1) consist of three dots rotating about a fixed point and two sets of two dots that are repetitively flashed for brief periods of time on either side of the rotating dots. Even though the dots are all in perfect alignment, subjects report a strong lag-effect: the flashed outer dots appear to lag behind the continuously lit inner dots [6, 2].

In all experiments described here, single dots subtend 0.4 degrees of the visual field and their centres are separated by 1.5 degrees. The whole stimulus of seven dots measures 9 degrees across and rotates at 25 rotations per minute. Stimuli were generated on a Silicon Graphics Indigo2 system and rendered on a monitor with a 72 Hz vertical refresh rate.

In our first experiment we vary the frequency with which the outer dots are flashed (duration fixed at 0.042 s, luminance at 57.8 cd/m^2), in the second the duration of individual flashes of the outer dots (frequency fixed at 1 Hz, luminance at 57.8 cd/m^2) and in the third, the luminance of the inner dots (frequency and duration fixed at 4 Hz, 0.042s respectively). Subjects (volunteers from the department, including the authors) were seated in a darkened room, at a distance of 70cm in front of the monitor. Subjects fixated the centre of the screen, which coincided with the rotation axis of the seven dots.

Subjects adjusted an offset-angle between inner and outer dots until they perceived them to be in alignment (See figure 1). The offset-angle was stored when the subjects confirmed the percept of alignment. The order of presentation of trials was randomised across all parameters within an experiment and left and rightward rotations were chosen at random. Moreover, a random initial offset angle between the inner and outer dots was chosen for each trial. The stored offset angles are the angles needed to null the lag-effect and are therefore interpreted as the negative of the real flash-lag angles. The figures show the means of the offset angles with standard error bars. In terms of a latency-correction mechanism, each lag-angle corresponds to a latency. This can be calculated by dividing the lag-angle by the fixed angular velocity; the figures show both measures of the lag-efffect.

Significant trends and significantly different means were tested with one way ANOVAs. The Pearson Product Moment was used as a measure of correlation.

3 Results

Due to the finite refresh rate of a monitor, one cannot speak of "continously lit" objects in this setup. In our experiments the inner three dots (see figure 1) are flashed too, albeit at the high rate of 72 Hz. In preliminary experiments we tested this setup and found that the flash-lag effect exists even when the stimuli are generated on a monitor rather than with the continuous light of LEDs (as in [2]). Moreover, the dependence on the angular velocity is similar to what has been shown for continuous light. That is, the effect increases linearly with angular velocity such that the latency-correction measured in miliseconds is approximately constant and on the order of tens of miliseconds (not shown).

To allow a comparison of different subjects we first determine how well a subject can align the stimulus when all dots are shown at the same (maximum) frequency of 72 Hz. To the observer, this looks as if all seven dots are continuously lit. Similarly, we determined the baseline for long durations: the outer dots were shown for 0.5 seconds at a frequency of 1 Hz. Subjects showed no significant differences between these situations, but, to our surprise, the baseline lag was significantly different from zero for some subjects (Figure 2).

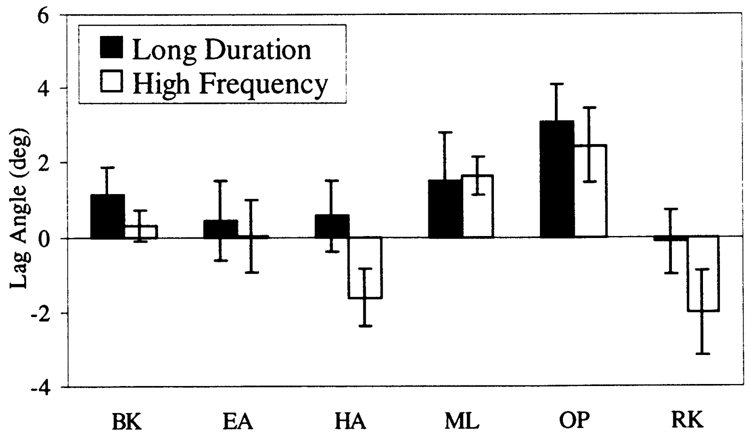

Figure 2: Baseline lag effect. A high-frequency and a long duration baseline. In both conditions no lag would be expected. The error bars show the 99% confidence limits.

3.1 Flash Frequency

In terms of a prediction mechanism, the lag-angle is presumed to be caused by the fact that stimuli which are seen only occasionally, are unpredictable. Our first experiment answers the question: "How frequently must stimuli be shown to be 'predictable'?" Figure 3 shows that the lag angle falls off exponentially with the flash-frequency. This effect is significant for all subjects ($p < 0.01$) and the fall-off is well described (Mean correlation $\bar{r} = 0.95$) by an exponential.

The dependence on frequency is remarkably similar for all subjects. In terms of a prediction mechanism, the exponential fall-off can be interpreted as follows: the higher flash-frequency increases the information the visual system has about the outer dots. This allows a more accurate perception of their speed and hence a better prediction of their future position. Due to this prediction the difference in perceived position between the continuously shown inner dots and flashed outer dots disappears.

In conflict with this interpretation is the fact that there is no *sharp* transition from the perception of a lag to the perception of alignment. Such a dependence is expected because it should be possible to divide stimuli into the categories 'predictable' and 'non-predictable'. The fact that this is not possible is furthermore strengthened by the observation that the variance in the perceived lag angles is not significantly ($p > 0.05$) correlated with the frequency for any of the subjects. This would imply that, even though the stimulus becomes less predictable, the latency-correction mechanism does not make mistakes more often.

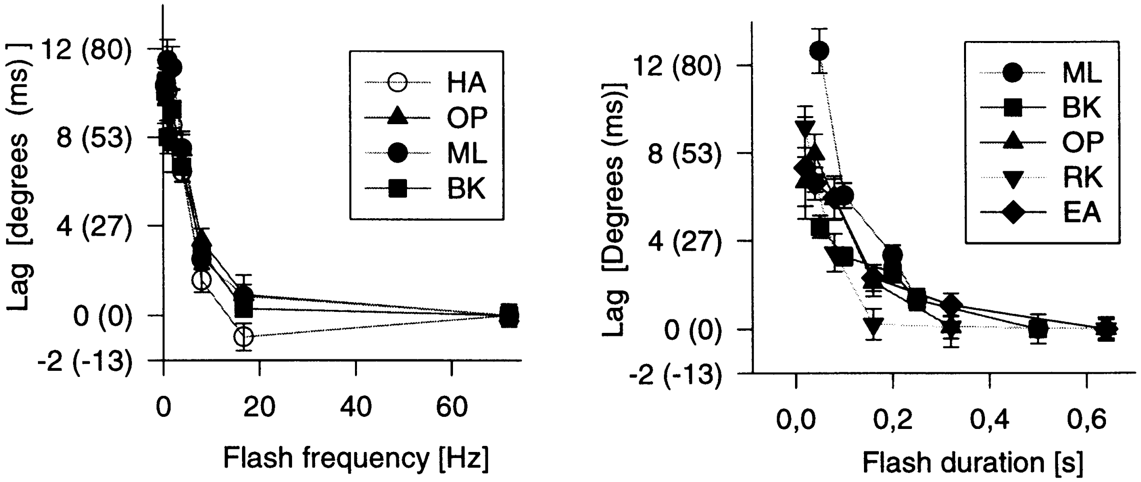

Figure 3: **Left)** The dependence of the lag angle on the frequency of the flashes. Lag angles are expressed as diffferences between the lag angle measured at a particular frequency and the baseline lag-angle shown in figure 2. The angle falls off exponentially with the flash frequency. **Right)** The dependence of the lag angle on the duration of single flashes. Lag angles are expressed as differences between the angle measured at a particular duration and the lag angle perceived at the longest duration. The fall-off is exponential.

3.2 Flash Duration

In a second experiment we pose the question: "how long does the prediction mechanism have to observe a stimulus to be able to predict its motion?". Any mechanism that aims to predict the future of a system must observe that particular system for a period of time. By decreasing the time during which the outer dots are shown (while keeping the frequency constant), the hypothetical prediction mechanism gets less information to base its prediction upon. Figure 3 shows how this affects the lag angle. The curves are shifted by the amount of lag that is left at long durations. Durations longer than these no longer influence the lag angle ($p > 0.01$).

The figure shows that the lag angle decreases as a function of the duration of the flashes. This effect is significant for all subjects ($p < 0.01$) and, again, well described by an exponential (Mean correlation $\overline{r} = 0.98$). The figure shows that the prediction mechanism is differentially sensitive to stimuli with a duration of up to 0.5 seconds. The correlation between duration and variance in the lag-angle was tested but did not reach the ($p = 0.05$) significance level for any of the subjects.

3.3 Stimulus Luminance

If the prediction mechanism's purpose is to correct for the presence of delays in the visual system, it should know about different delays. In other words, when a particular signal travels slowly from retina to cortex its source will have travelled much farther in real space during this delay. A useful latency-correction mechanism should adapt the amount of its forward prediction to the delay of the neural signal.

It is well known that low luminance signals are perceived with an increased latency (see for instance [7]). In line with the reasoning above, this implies that changes in luminance should lead to changes in the lag angle. Specifically, if the luminance of the inner dots is reduced, their latency increases. Hence, to correct for this longer latency, the hypothetical prediction mechanism should predict the three dots further forward and thus lead to an increase in the lag angle. Figure 4 shows that, rather than increasing at lower luminances, the lag effect *decreases*. This effect is significant for all subjects ($p < 0.01$). This implies that the hypothetical latency correction mechanism only works for a single stimulus luminance.

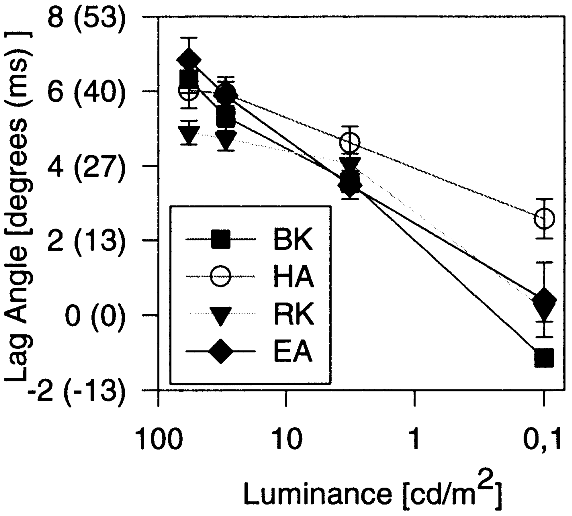

Figure 4: The dependence of the lag angle on the luminance of the inner dots.

4 Discussion

Our experiments show that the properties of the hypothetical latency correction mechanism are peculiar. Most directly, when confronted with stimuli that reach the cortex with different latencies, it fails to adapt its correction to this situation. This implies that the correction is only correct for one particular latency.

Secondly, the continuity of the dependencies on the temporal parameters is problematic as prediction would normally be expected to be an all-or-nothing phenomenon. Either the system has received enough information to predict the speed of the outer dots as well as the inner dots (and hence the lag-angle is zero), or there is not enough information and no prediction is done. In the latter case the lag-angle should be equal to the latency times the angular velocity. The hypothetical latency-correction mechanism investigated here, however, always makes a prediction but varies the amount by which it corrects for the incurred latency.

We propose that not a prediction of the inner dots is responsible for the lag effect, but rather the *delay* of the outer dots. Such a delay leads to a perceptual lag angle because during the extra time it takes for the neural signal from the outer dots to travel to the cortex, the inner dots will have moved on. The lag angle will equal the product of the *difference in latency* times the angular velocity.

The interpretation of figure 4 is now straightforward and supports our view. Lowering the luminance of the inner dots increases their latency. This decreases the difference in latency between the inner and the outer dots and hence a reduction of the lag-angle follows. The dependence of the lag angle on the temporal parameters (in figure 3) can now be interpreted as showing the dependence of the latency on the duration and frequency of a stimulus. This dependence is an ad-hoc assumption so far, but we present evidence from the literature to support it.

First, to support the view that differential delays can lead to spatial offsets, we note that a temporal delay between the presentation of two moving half-lines is perceived as a spatial offset [5].

Secondly, we need evidence that the outer dots are processed with a longer latency. As there are several ways in which the outer dots are different from the inner dots, there is a number of possible causal factors. First we note that a simple explanation such as a duration-dependent retinal latency is probably not correct. This can be seen from the data in [3] where the time-to-peak latencies of cells in cat primary visual cortex clearly *increase* with the duration of a stimulus.

Recent evidence from human psychophysics [1], on the other hand, shows that a direction of motion is determined more rapidly from stimuli that are perceived to be in apparent motion than from a single stimulus that appears to jump from one position to the next. Translating to our experiment this means that the perceptual latency of the inner dots (which are in apparent motion) is smaller than that of the outer dots (which appear to jump from one place to the next). By increasing the frequency or the duration (figure 3) of the outer dots, these dots appear to move more smoothly. In accordance with the results in [1] their latency is decreased which leads to a reduction of the lag-effect.

Our view is also supported by experiments that show that processing is facilitated in regions in which other stimuli are present or were present recently [8]. Such a local facilitation effect has been proposed to underlie illusory line-motion [4]. In terms of the flash-lag experiment, the outer dots appear in regions in which the time and distance between subsequent dots is larger, consequently the facilitation is smaller. This leads to an increase in latency and hence a lag-effect.

5 Conclusion

The parameter dependencies of the flash-lag effect are quite unlike what one would expect if a prediction mechanism were responsible. There is no sudden transition from "predictable" to "unpredictable" nor is there a correlation between the predictability (i.e. the temporal parameters) and the uncertainty in the prediction. Finally, the hypothetical latency correction does not adapt to different latencies in the visual system. We conclude that the flash-lag visual illusion is not caused by a latency-correction mechanism.

Instead, we propose that the illusion is the result of differential delays in the visual system. Evidence from various sources indicates that these differences are caused by the (non-linear) interaction of the stimuli in the visual system. Stimuli that are nearby in time and space speed up each others perception. This leads to a relative decrease in latency for the inner dots in the flash-lag illusion and hence to a perceived lag-angle between the inner and outer dots.

Coming back to our starting point, our findings show that the forward prediction and anticipation that is evident in our actions while playing a ball game has not been demonstrated in perception. Taking the biological solution as a lead how to develop an artificial system, this indicates that the correction for latencies in the information processing system is best left to the action part of the control system. On the other hand, the interactions in the perception of visual stimuli can be seen as a mechanism to direct appropriate resources to areas of interest in the visual field. Such an approach may also be fruitful in artificial systems.

References

[1] J. Allik and K. Kreegipuu. Multiple visual latencies. *Psychological Science*, 1997. To appear.

[2] M. V. C. Baldo and S. A. Klein. Extrapolation or attention shift? *Nature*, 378:565–566, 1995.

[3] J. Duysens, B. Gulyás, and H. Maes. Temporal integration in cat visual cortex: a test of Bloch's law. *Vis. Res.*, 31:1517–1528, 1991.

[4] O. Hikosaka and S. Miyauchi. Voluntary and stimulus-induced attention detected as motion sensation. *Perception*, 22:517–526, 1993.

[5] M. Morgan. Pulfrich effect and the filling in of apparent motion. *Perception*, 5:187–195, 1976.

[6] R. Nijhawan. Motion extrapolation in catching. *Nature*, 370:256–257, 1994.

[7] J. Roufs. Perception lag as a function of stimulus luminance. *Vis. Res.*, 3:81–91, 1963.

[8] B. A. Steinman, S. B. Steinman, and S. Lehmkuhle. Visual attention mechanisms show a center-surround organization. *Vis. Res.*, 35:1859–1869, 1995.