

thorough analysis of a more comprehensive data set.

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## Moving ahead through differential visual latency

The time it takes to transmit information along the human visual pathways introduces a substantial delay in the processing of images that fall on the retina. This visual latency might be expected to cause a moving object to be perceived at a position behind its actual one, disrupting the accuracy of visually guided motor actions such as catching or hitting, but this does not happen. It has been proposed that the perceived position of a moving object is extrapolated forwards in time to compensate for the delay in visual processing<sup>1–3</sup>.

We have studied the spatial misalignment perceived between moving and strobed objects and find that it varies systematically with the luminance of the objects. Our results favour an explanation for these perceived misalignments based on differential visual latencies, rather than on motion extrapolation. Thus, accurate visually guided motor actions are likely to depend on motor instead of perceptual compensation.

Evidence for a mechanism based on motion extrapolation<sup>1–3</sup> comes from the flash-lag phenomenon<sup>4</sup>, in which a continuously moving object is perceived to be ahead of a stationary strobed object when the two retinal images are physically aligned. But because visual latency varies according to the properties of a stimulus, including its luminance<sup>5–9</sup>, this mechanism would have to compensate appropriately for a range of stimulus-dependent variations in latency to ensure that real-time, visually guided responses are accurate. An alternative, previous

explanation, invoking a longer delay for the processing of a flashing stimulus, was based on attentional mechanisms<sup>10</sup>.

According to the hypothesis based on differential visual latencies, the observed spatial lead of the moving central segment in Fig. 1a is directly proportional to the difference between the latencies of the strobed and the moving central segments. For a given stimulus, the visual latency varies inversely with its luminance<sup>5–9</sup>, so the observed spatial lead in the flash-lag paradigm should vary according to the luminance of the strobed and moving central segments. Increasing the luminance of the moving central segments but not that of the strobed segments should decrease the delay of the moving central segment ( $d_m$ ) while

that of the strobed segment ( $d_s$ ) remains constant. The latency-difference hypothesis therefore predicts that the observed spatial lead of the moving central segment should increase.

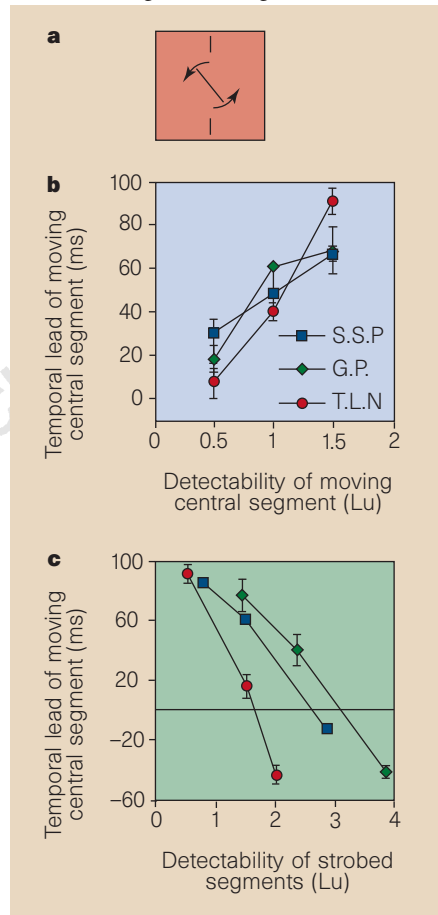
To test this prediction, we measured the spatial lead of the moving central segment as a function of the detectability of the central segment while keeping the detectability of the strobed segments constant. Here we use detectability to refer to the number of log units of luminance (Lu) above the detection threshold; detectability of the strobed segments was 0.3 Lu for subjects S.S.P. and G.P., and 0.5 Lu for T.L.N. The temporal lead of the moving central segment averaged across subjects increases systematically from 20 to 70 ms when its detectability increases by 1.0 Lu (Fig. 1b).

Increasing the luminance of the strobed segments while keeping that of the moving central segment constant should decrease  $d_s$ , while  $d_m$  remains constant. The latency-difference hypothesis predicts that the observed spatial lead of the moving central segment should decrease and, if the luminance of the strobed segments is high enough, the moving central segment should be perceived to lag behind spatially. We tested this prediction by measuring spatial lead as a function of the detectability of the strobed segments, while keeping the detectability of the moving central segment constant (1.5 Lu above the detection threshold for subjects G.P. and T.L.N., and 0.8 Lu for S.S.P.). The observed temporal lead of the moving central segment averaged across subjects decreases systematically from 80 to –30 ms as the detectability of the strobed segments increases by 1.5 to 2.0 Lu (Fig. 1c).

These results support predictions of the latency-difference hypothesis and show that the motion-extrapolation mechanism does not compensate for stimulus-dependent variations in latency. Indeed, theoretical calculations show that the putative motion-extrapolation mechanism must be under-compensating by at least 120 ms to account for the data in Fig. 1. But a motion-extrapolation mechanism that does not adequately compensate for variations in visual latency would not appreciably improve the accuracy of real-time visually guided behaviour.

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**Figure 1** Luminance-dependent misalignments between moving and strobed targets. **a**, The stimulus was a continuously rotating central segment (40 rev min<sup>-1</sup>) and two flanking strobed segments (5 ms). **b**, The observed temporal lead of the moving central segment is shown as a function of its detectability (0 = threshold) for three subjects (S.S.P., G.P. and T.L.N.). Positive values on the y-axis represent a temporal lead in perceiving the moving central segment relative to the strobed segments. The observed spatial lead was converted into a temporal lead by dividing it by the velocity of the moving central segment. **c**, The observed temporal lead of the moving central segment is shown as a function of the detectability of the strobed segments (0 = threshold) for the same subjects.

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