A comparison of pursuit eye movement and perceptual performance in speed discrimination

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1. INTRODUCTION

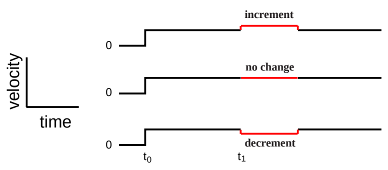
A central goal of sensation and perception is to direct our interactions with the environment. During most voluntary motor actions that are driven by sensory input we consciously experience an internal representation of the visual world. This leads to the question how faithful this internal representation is, and how precise our actions are compared to this reference. To answer that question, we studied the relationship between the perceived speed, which is the experiential representation of the stimulus, and the speed of smooth-pursuit eye movements, the motor action.

We determined psychophysical thresholds for detecting small perturbations in the speed of Gabor patterns (1 cycle deg^{-1}) moving at a base speed of 4 deg s^{-1}. At the same time we recorded eye-movement traces and used an ideal-observer analysis to compute analogous ’oculometric’ thresholds.

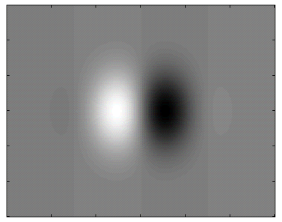
Our results show a remarkable agreement between perceptual judgments for speed discrimination and the fine gradations in eye-movement speed, with psychophysical and oculometric functions exhibiting the same slope. However, there was no correlation between perceptual errors and eye-movement errors on a trial-by-trial basis. We conclude that the motor system and perception share the same constraints in their analysis of motion signals, but they act independently and have different sources of noise.

2. METHODS

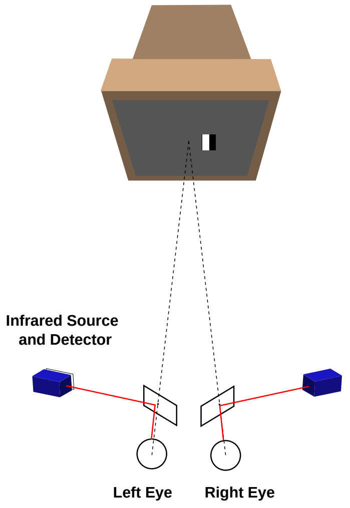
Velocity Profile



Spatial Profile



Experimental Setup

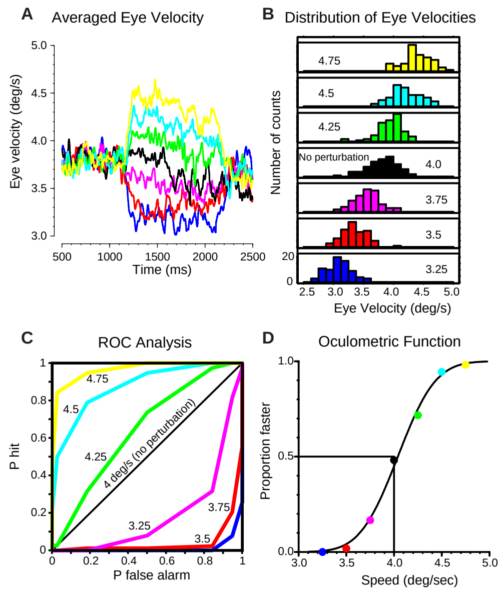


Visual Stimuli: Small Gaussian vignetted patches of achromatic sinusoidal grating were used as stimuli. The onset of base speed of the target begins at t_0 then at time t_1 the speed is ramped up or down to a new speed (the perturbation speed) that lasts for 500 ms before it is ramped back to the base speed. The subject’s task is to track the target as closely as possible. At the end of each trial the observer is required to make a decision whether the target moved faster or slower during the perturbation period in the middle of the target motion. In this way we collected psychophysical data and eye movement data on the same trials.

Eye Movement Recording: The position of one eye was measured with a single channel Purkinje-image infra-red eyetracker[29] (Fourward Technologies - Generation V). Viewing was binocular with natural pupils, each eye’s view was through a 45 degree angled glass plate with greater than 90% transmittance.

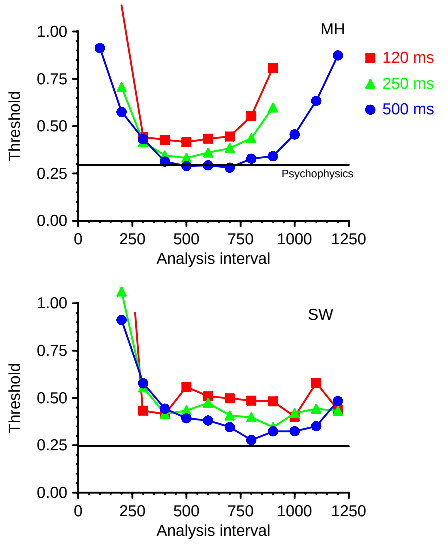
Procedure: Each session consisted of 56 or 84 trials. Within the trials of each session we included all the perturbation speeds and both starting sides (left or right), randomly mixed.

3. ROC-ANALYSIS



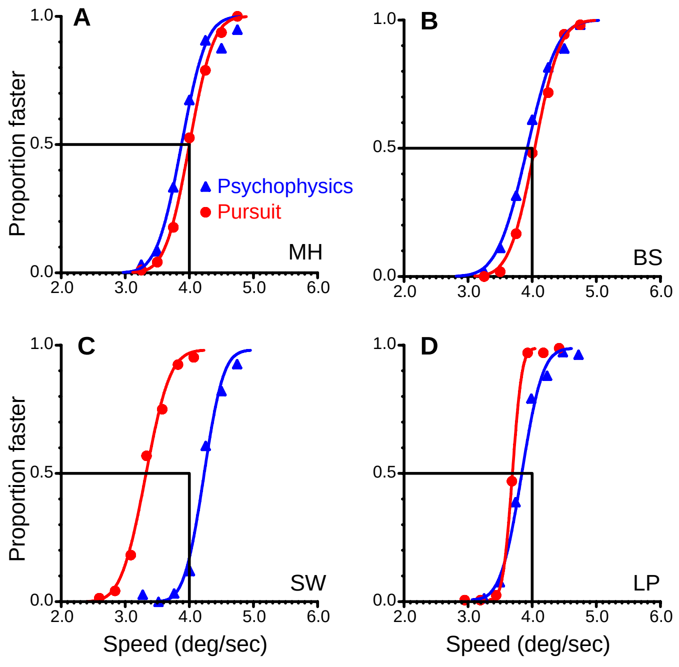
(A) Average eye velocity across all trials for observer MH for stimuli moving at a base speed of 4 deg/s. Different perturbation speeds are indicated by different colors. The black horizontal bar indicates the time window used for the ROC-analysis. (B) Distributions of eye velocities from single trials. (C) Responses from the no perturbation condition were used as the baseline and for 20 criterion speeds we constructed a standard ROC curve for each of the perturbation speeds. (D) The area under each of the curves gives the proportion of “correct” responses. From these, we constructed an oculometric function. The slope of the function measures discriminability.

4. TIME COURSE



For the functions above right, we used a 500 ms analysis interval centered at 500 ms after perturbation onset. Variations in the duration and offset of that interval have little effect on the slope of the oculometric function.

5. RESULTS



Comparison of psychometric and oculometric functions for four observers. Discrimination performance, which indicates the reliability with which each observer can detect the change in speed from the base speed of 4 deg/s, is given by the slope of the psychometric and oculometric functions. Slopes are identical for both functions for observers MH and BS. For observer SW, the psychometric function is slightly steeper, while for observer LP the oculometric function is much steeper.

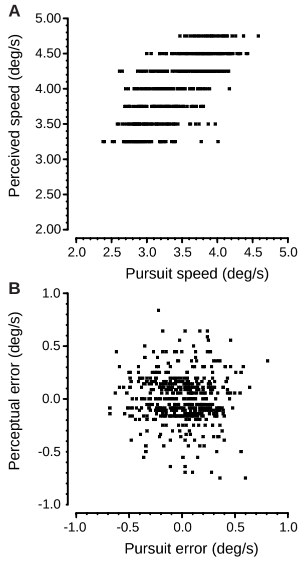
These results show that the fidelity of the motor system can perfectly match that of a sensory system. This agreement in absolute thresholds is actually difficult to reconcile with a model of perception and motor control, where initially the visual system analyzes the speed of moving stimuli, and that speed estimate is then supplied to the motor system to control behavior. Neural computations at all levels are prone to noise.

Our results rule out the possibility that simple measurement noise of the eye movements may give rise to differences in the fidelity. Another source of noise, motor noise from the oculomotor plant, might manifest itself as a reduction in pursuit fidelity compared to the perceptual fidelity. In our experiments this does not seem to be the case.

Our results suggest that the magnitude of the noise common to both processes, presumably introduced by the analysis of visual motion, is so large that the separate noise sources are negligible. Alternatively, the amount of noise added separately to the two systems could, incidentally or not, be of the same magnitude.

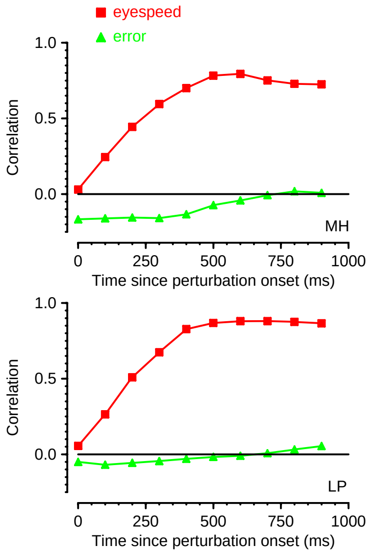
A much more powerful way to investigate the relationship between the circuits driving perception and action is to look at the correlation between the perceptual and pursuit errors made on individual trials. If faster perceived speed goes along with faster eye movements on individual trials, this would support the notion that both subsystems are driven by the same circuitry and signals. A lack of correlation would suggest that independent subsystems are responsible for perception and action.

6. CORRELATION



(A) Correlation between pursuit speed and perceived speed on 500 individual trials. Perceived speed was based on a 7-point category rating scale, which was translated into the seven absolute speeds used here. The observed correlation is high ($\rho = 0.70$, $p < 0.0001$), caused by the fact that both quantities correlate highly with the physical speed of the stimulus ($\rho = 0.82$ and $\rho = 0.87$, respectively, $p < 0.0001$).

(B) Partial correlation between pursuit errors and perceptual errors on the same 500 trials. the correlation completely disappears ($r = -0.038$, $p > 0.1$). This held for all four observers.



This lack of correlation did not depend on the analysis interval. The red curve shows how the correlation of eye speed with subjective speed emerges during the first 500 ms of the perturbation interval. During the whole time, there is no significant positive correlation between the eye movement error signal and perceived speed error, once the physical perturbation speed is cancelled out.

7. SUMMARY

- The fidelity of the motor system can match perceptual fidelity.
- Perceptual and motor performance were uncorrelated on a trial-by-trial basis.
- The circuitry driving unconscious behavioral actions is effectively independent of the circuitry controlling our conscious perceptual experiences.