Quantifying noise reduction in sensory-motor processing

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In tasks where precision is at a premium, the brain must reduce the impact of internal noise sources in sensory estimation by integrating incoming stimulus information across neural populations and across time. To study how the brain reduces noise, we added noise at the sensory input and measured its impact on behavior. In sensorimotor systems like pursuit, where eye movements are a reliable read-out of the brain’s estimate of the motion of a visual target, behavior can reveal the underlying computation of target direction and speed from incoming visual motion signals. To probe how the brain integrates visual motion signals, we performed pursuit experiments in which we rewarded monkeys for tracking targets that moved stochastically. We had two goals for these experiments.

Our first goal was to determine how adding noise designed to increase variation in sensory estimates of target direction or speed would affect motor performance. In previous work, we put forward the hypothesis that variation in pursuit initiation is dominated by variation in the underlying sensory estimation of the target’s trajectory. We demonstrated that behavioral variation had the appropriate form and scale predicted from variations in visual estimates of target direction and speed and also that the time course mutual information between the eye movement and the stimulus is highly correlated with the time course of stimulus information signaled by motion-sensitive visual cortical neurons. In those experiments, the components of the target, a pattern of bright “dots” against a dark background, all moved coherently at the same speed and in the same direction. In the present experiments, we selected the direction or speed of each dot in the pattern randomly at each time step from a distribution of potential trajectories. This created a target in which each dot did a random walk in time about the same central trajectory, and at any point in time there was a distribution of dot directions or speeds within the target. We found that variation in pursuit direction and speed scaled linearly with the variance of stimulus pattern speed or direction even when the motor task was held constant. This result supports the hypothesis that sensory variation is the dominant source of behavioral variation in pursuit and further suggests that the visual estimate of target motion is sensitive to spatial variation in motion inputs.

Our second goal was to measure the temporal filter applied to incoming visual motion signals to drive pursuit. To isolate the temporal processing, we used targets in which each dot in the target performed an identical random walk about a central trajectory such that motion was spatially uniform but temporally stochastic. We computed the optimal linear filter between target and eye movement. The linear model did a surprisingly good job at predicting eye velocity, accounting for up to 70% of eye velocity variance. Filters had a width of about 25ms (full width at half maximum), consistent with the effective temporal sampling estimated from the first experiment. Stimulus manipulations that increased the frequency bandwidth of the stimulus also tended to narrow temporal filters slightly. We also found that filter shape did not change between the initial open-loop (sensory-driven) portion of the eye movement and the later closed-loop (feedback available) portion of the pursuit response.

Our results demonstrate that pursuit movements are well-predicted from simple models of spatial and temporal integration of incoming visual motion signals. Through an analysis of variation, we have shown that behavior can be closely tied to the brain’s sensory estimates of target trajectory. Our measurement of the temporal filter between target and eye velocity provides a strong constraint for models of the brain’s decoding of visual motion signals at the system level.