Exponential function

Model parameters

3 stimulus signal-to-noise ratios (SNR)

List of parameters for an experiment with 9 different conditions:

- Stimulus dynamics
- Control delay ("cd")
- Sensory delay ("sd")
  - "ca": std of Gaussian in deg
- Control noise
- Control cost ("r": a.u.)
- Sensory uncertainty

Parameters vs. Model

- None
- Fixed to 250ms (1)
- Free (1)
- Fixed to 60ms (1)
- Fixed to 0.1 deg (1)
- Free (1)
- Fixed to 0.1 deg (1)

Continuous psychophysics can quickly provide an estimate of uncertainty [Bonnen et al. 2015]. However, without considering a motor model, the uncertainty measurements are orders of magnitude off.

Sensory and motor sources of delay in visuomotor tracking: a model for continuous psychophysics

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Measuring sensory uncertainty rapidly and accurately with continuous visuomotor tasks.

Traditional methods – such as 2-alternative forced choice or estimation tasks – assume that perception is sampled from an underlying internal distribution induced by the stimulus. [Green & Swets, 1966]. Sensory uncertainty is then measured as the uncertainty (e.g. standard deviation) of the internal distribution. However, these traditional methods require long repetitive task paradigms.

Continuous psychophysics can quickly provide an estimate of uncertainty [Bonnen et al. 2015]. However, without considering a motor model, the uncertainty measurements are orders of magnitude off.

Hypothesis: accounting for motor costs in modeling continuous visuomotor behavior gives better measures of sensory uncertainty.

Continuous psychophysics reveals a longer delay and integration with more stimulus uncertainty.

Cross correlation kernel measures the correlation between the target's velocity and the pointer's velocity at various time lags.

As the stimulus becomes harder to see, the cross-correlation kernels become wider and delayed.

Model fits

Exponential fit to human kernels

Gamma fit to human kernels

Model fits

Kalman Filter integrates uncertain information across time.

Optimal control (LQG) adds costs for making a control movement.

Models that include motor costs can be differentiated from pure sensory integration models by their cross-correlation kernels.

We simulate two models and observe their qualitative features.
- Kalman model optimally integrates noisy sensory information.
- LQG model adds a control module that penalizes big movements.

The Kalman model is fit better by the exponential, while kernels models with control cost were fit better by the gamma.

There is a systematic increase in width and delay of the kernel with both sensory uncertainty and motor cost.

Kalman Filter

Full visuomotor model

LQG (Linear control, quadratic cost, Gaussian noise) finds a linear control that minimizes the task objective. ([Todorov, 2002])

Sensory uncertainty estimated from LQG (red) is comparable to those of other tasks. Measurements from the Kalman model (blue) are log units off.

Model with motor cost recovers uncertainty measures comparable to traditional tasks.

Main Takeaway

An optimal control model – which includes controls with cost in addition to sensory integration – accounts for the shape of the cross-correlation kernels and recovers more accurate measures of sensory uncertainty.