

# Timing based on stochastic neural and sensory processes

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Many perceptual processes and neural computations, such as speech recognition, or motor control and learning, depend on the ability to measure and mark the passage of time. However, the neural mechanisms that make such temporal judgements possible are unknown. A number of different hypotheses have been advanced, all of which depend on the known evolution of a neural [1] or psychological state, possibly through oscillations or the gradual decay of a memory trace [2,3]. We suggest a new model, which instead exploits the fact that neural and sensory processes, even when their precise evolution is unpredictable, exhibit statistically structured changes [4,5]. We show that this structure can be exploited for timing, and that reliable timing estimators can be derived from the statistics of the processes. This framework of decoding time from stochastic processes allows for a much wider array of neural implementations of time estimation than has been considered so far, and can simultaneously emulate several different behavioral findings, which so far have only been understood in psychological terms.

We abstract neural and sensory processes to stationary Gaussian Processes (GPs), and show that, on the basis of observations of a collection of such processes at two distinct points in time, the GP likelihood gives rise to a probability distribution over elapsed time (Fig. 1). Under relatively loose assumptions, estimators derived from this distribution follow the Weber law of timing.

Formulating the inference of elapsed time within the above framework naturally allows stimulus statistics to interact with the timing mechanism. Two compelling recent psychophysical observations [6,7] are emulated by manifesting changes in the stimulus as changes in the temporal spectrum of a sense-driven subset of the stochastic processes. This results in estimators that show biases towards over- or under-estimating the elapsed time during stimulus presentation that are similar to those observed in humans. Preliminary psychophysical results of our own (Fig. 2) further show that subjective time dilation or contraction, known to depend on the temporal frequency of deterministic stimuli, can also be driven by stochastic stimuli.

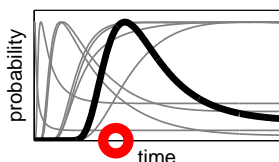


Figure 1: Likelihood curves from individual stochastic processes (*gray*) are weakly informative about elapsed time; combining curves from multiple processes, at multiple time-scales, results in a distribution (*black*) which peaks at the right time.

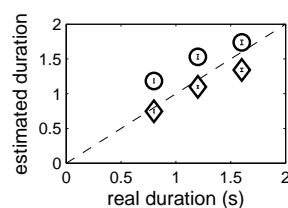


Figure 2: *Circles*: Observers adjusted the length of a slow stochastic process to match the length of a fast process. *Diamonds*: vice versa.

## References

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