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Progress and decay – An information-theoretical view on the Janus face of time

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Accurate representations of time are crucial for a wide range of brain functions such as speech recognition and the planning and execution of coordinated movements. While the neural basis of these representations remains debated, there is a large body of psychological studies probing the capabilities and limits of time perception. A recurring result of these experiments was that the just noticeable difference between two temporal intervals increases linearly with the duration of the intervals, which is referred to as Weber's law, or the "scalar property." However, the neural basis of this law remains elusive and it could not be reproduced by any of the existing models of time perception, although we have recently proposed a model that approximates this law in a wide range of durations [1].

Here, we look at the scalar property from an information-theoretical point of view [2]. We employ general Gaussian random processes as a model for the neural representations of time with temporal changes in both the mean, variance, and covariance; we then use Fisher information to compute the theoretical lower bound for timing errors that give rise to a finite just noticeable difference. Under quite natural assumptions (mean and variance linearly increasing in time, exponentially decaying correlations), we found a hierarchy of temporal information in those three moments: The lower bound for the timing errors scales with the square root of the duration of the estimated interval if only the information from the mean is used, but is linear in the duration when relying on the variance alone, and even increases exponentially with the interval duration when using only the covariance.

This result is in contrast to earlier work [2], which claimed that the linear increase in timing errors is explained by simultaneous observation of Gaussian processes with exponentially decaying covariance functions of different decay times. We could show, using a combination of analytical and numerical methods, that this is only the case if the time constants of the covariance decay are much larger than the interval to be estimated, because the increase of the timing errors is inherently exponential in the interval duration. Furthermore, we tested this general statistical framework on the neurocomputational model earlier proposed, which is based on multiple synfire chains [1], and could reproduce the results that were obtained by neural optimization (scalar property in a limited time regime, superlinear increase of errors at longer times).

The present framework highlights the possibility to estimate time intervals from various sources, both systematic change of states in the brain and also the decay of such neuronal signals or signal correlations over time. While most information could be captured using only the systematic changes in the processes, the psychophysical results provide evidence for the notion that information is conveyed by the variance alone. As neocortical cells have been shown to provide a population rate code with high temporal resolution when working in a variance-driven regime [3], our results suggest that this processing mode is relevant for the perception of time.

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