Hierarchy of cortical population characteristic timescales inferred from field potentials

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Summary

Neuronal populations across the macaque cortex exhibit intrinsic characteristic timescales in their spiking fluctuations. Specifically, sensory areas have shorter timescales of spiking autocorrelation (i.e., faster decay), while frontal areas have longer timescales [1]. Importantly, these regional differences predict working memory function, suggesting possible physiological mechanisms for how populations temporally maintain information [2]. Extending measurements of population timescales across many brain regions would considerably broaden our understanding of neurodynamics and how they support behavior. However, it is prohibitively expensive and technically challenging to record single units across the whole macaque cortex under different tasks, and impossible in the human brain due to the scarcity of single-unit recordings, even in rare clinical settings.

Here we infer neuronal population timescales from field potentials recorded via electrocorticography (ECoG) grids across the macaque cortex. In frequency domain, the power spectral density (PSD) of field potentials often have a 'knee' [3] connecting two distinct power law-like regimes. The frequency at which this knee occurs corresponds mathematically to the time constant of autocorrelation decay in time domain. Applying a spectral parameterization tool we developed on 8 whole-cortex ECoG recordings from 2 monkeys [4,5], we find that ECoG timescales are tightly correlated with the reported spiking fluctuation timescales in select cortical areas from [1] (rho=0.884, p=0.008). We extend the analysis across cortex and find a U-shaped trend along the anterior-posterior axis, with the shortest timescales occurring in sensorimotor regions. Finally, we find that timescales decrease by half from eyes open to eyes closed resting. We validate the method with simulation of varying timescales, and discuss results pertaining to the scale-free nature of neuronal activity. In summary, this work offers a method for characterizing neuronal population timescales in ECoG, which can be extended to human datasets, as well as possibly M/EEG and field potential data in other model organisms.

Additional Detail

Motivation & Significance: Putative single unit activity remains expensive and difficult to sample across many brain regions in larger animal models, and is rarely justified in human subjects even under clinical settings. While spike timing and single cell tuning studies require well-isolated neurons, population-level variables should theoretically be reflected in meso- and macro-scale recordings, such as local field potentials (LFP) and surface ECoG, which largely reflect local aggregate synaptic currents [6]. We set out to test this explicitly, with a specific focus on the intrinsic timescale of fluctuations in neural population activity. Recent studies have shown anatomically specified and functionally relevant timescales across brain regions (Fig. 1a) [1,2]. Pragmatically, being able to infer the local timescale of fluctuation across the cortex – and doing so easily – would significantly accelerate our ability to directly map behavior to neurophysiological processes without invasive single neuron recordings, and we could make further inferences using a large body of existing field recordings. Additionally, brain-computer interface (BCI) applications that currently rely on single neurons (*e.g.*, neuroprosthetics) would benefit from the rich information repertoire embedded in field potentials. This could reduce the need for prolonged cell recordings, minimizing patient risk. In short, decoding the physiological information of the aggregate field potential, such as population timescales, would allow us to measure brain states in new ways, bridging the gap between cognitive and cellular neuroscience and drastically increasing our ability to relate fundamental brain processes to behavior as a result.

Method & Result: We have recently developed an open-source toolbox for parameterizing rhythmic and aperiodic components in the PSD of electrophysiological signals [3]. Apart from neural oscillations, field potential signals have a characteristic aperiodic background that can be described by an inverse power-law function at high frequencies ($1/f^{\chi}$) [7]. Additionally, there is often a 'knee' in the PSD connecting two disjoint power-law like regimes with different exponents. This curve is described well by a Lorentzian function (Fig. 1b), which we fit in addition to oscillatory peaks. Conveniently, the 'knee' parameter has a direct analytic mapping to the exponential decay constant (or half-life) of the autocorrelation function, which was explicitly fitted for population autocorrelation in [1]. We confirm the robustness of the analysis method with simulated data, either with exponential or power law decay in the autocorrelation function.

In this work, we fit the PSD for 128-channel whole-cortex ECoG recording from 8 sessions in 2 monkeys, and extract the timescale parameter from the frequency-domain 'knee'. Averaging across electrodes in the sub-regions available in [1], we find a close relationship between ECoG timescale and spiking timescale (Fig. 1c). This is robust across all 8 sessions, during eyes open and closed, as well as in the per-monkey and grand average (Fig. 1d). Interestingly, ECoG timescales do not equal to spiking timescales, but scale with a factor of 0.12 during eyes-open. Furthermore, we find that the power law exponent (χ), a measure of scale-free and potentially long-range dynamics, also correlate with spiking timescales, reproducing another result in [1]. Finally, we find a U-shaped trend of ECoG timescales along the anterior-posterior axis, minimized around the central sulcus, and that timescale across all electrodes decrease 2-fold (by half) when monkeys transition from eyes open to eyes closed state. These results represent a first step in mapping intrinsic timescales across regions of the cortex, which we plan to apply to human ECoG data recorded during various experimental conditions.

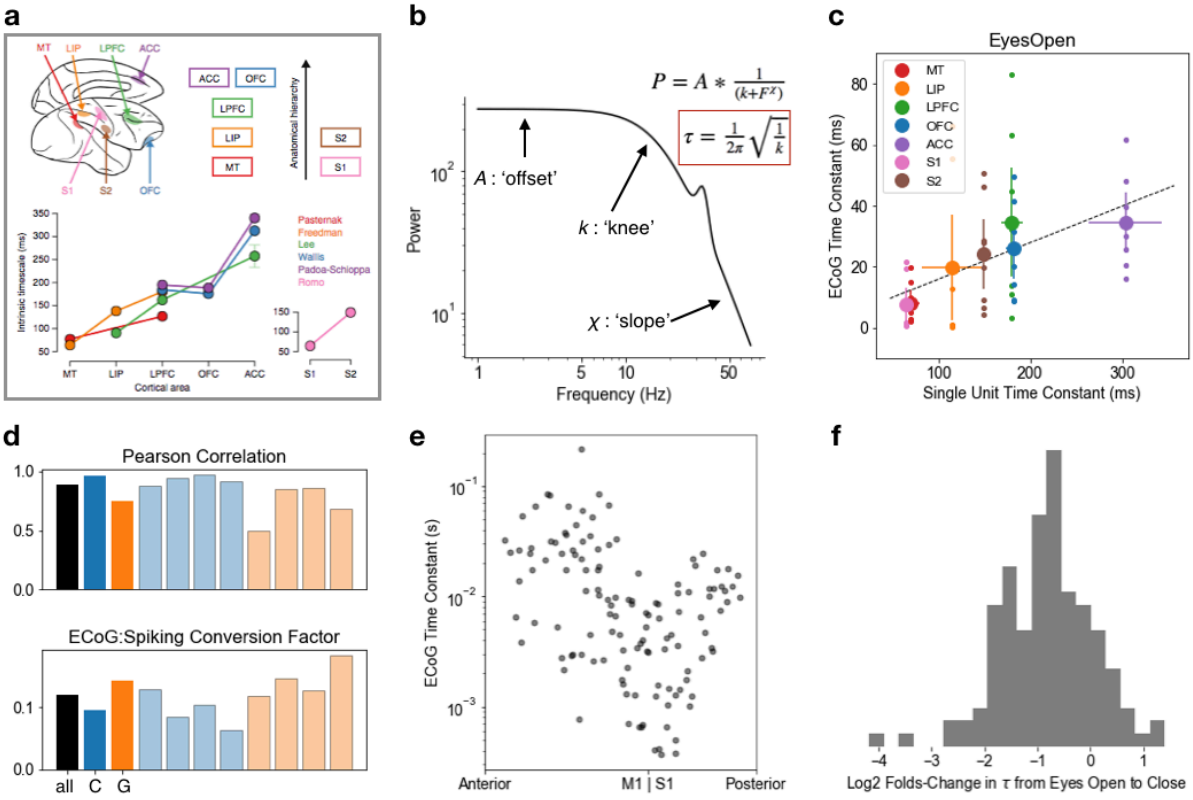

Figure 1. a) Intrinsic neuronal population timescale increases along cortical hierarchy (adapted from ref. 1). **b)** Spectral parameterization model fits a Lorentzian form to PSD; inset: equations for extracting characteristic timescale from spectral parameters. **c)** Correlation between grand average ECoG and spiking timescale across 8 sessions, small dots represent individual session fits, error bars show 95% confidence interval. **d)** Pearson correlation (top) and ECoG to spiking timescale conversion factor (bottom, i.e., slope of line in **c**) for grand average (black) and per-monkey average for Chibi (blue) and George (orange). Faded bars show individual session results. **e)** ECoG timescales along anterior-posterior axis show an U-shaped relationship, with sensorimotor regions showing the shortest timescales (M1 and S1 marked). **f)** ECoG timescale halves from eyes-open to eyes-closed resting.

References

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