Background: Synaptic LFP Analysis

1 The Filtered Poisson Process (FPP) Model

Extracellular signals (EEG, ECoG, LFP) are modeled as the summation of discrete synaptic events (Post-Synaptic Potentials, PSPs). Mathematically, this is expressed as a convolution between a spike train $S(t)$ (modeled as a Poisson point process) and a synaptic kernel $K(t)$ which defines the shape of the PSP:

$$V(t) = (S * K)(t) = \sum_j k(t - t_j) \tag{1}$$

Where t_j denotes the discrete spike times and $k(t)$ represents the synaptic kernel (e.g., a dual-exponential function representing AMPA or GABA currents). This formalism assumes that the LFP is primarily generated by the superposition of transmembrane currents.

2 The Ψ Pattern

To analyze the signal in the time domain, the Ψ pattern is introduced. It is defined as the negative derivative of the signal's autocorrelation function (R_{VV}):

$$\Psi(\tau) = -\frac{\mathrm{d}}{\mathrm{d}\tau} R_{VV}(\tau) \tag{2}$$

Theoretical analysis demonstrates that for FPP signals, $\Psi(\tau)$ recovers the temporal features of the underlying synaptic kernel $k(t)$. This property allows us to estimate synaptic rise and decay times directly from the raw LFP trace, providing a window into the circuit's temporal dynamics.

3 Spectral Parameterization

In the frequency domain, electrophysiological signals are characterized by a $1/f$ decay in power. We utilize the `specparam` algorithm (formerly FOOOF) to parameterize the aperiodic component of the Power Spectral Density (PSD).

The steepness of this decay is quantified by the **spectral exponent**. Mathematically, the spectral exponent is closely related to the to the temporal profile of the synaptic kernels composing the signal. In this context, slower kernels result in diminished high-frequency components, and therefore in a steeper spectral slope.

4 Synaptic Balance (EIB)

The core hypothesis of this project is that the **Excitation-Inhibition Balance (EIB)** acts as a modulator of signal dynamics. The physiological basis for this is the difference in kinetics between excitatory (AMPA) and inhibitory (GABA) receptors:

- **High Excitation:** The signal is dominated by fast AMPA kinetics. This results in noisier signals and a **flatter PSD slope** (lower spectral exponent).
- **High Inhibition:** The signal is dominated by slow GABA kinetics. This results slower signals and a **steeper PSD slope** (higher spectral exponent).

This relationship is robust and observable in both the spectral exponent (frequency domain) and the Ψ pattern duration (time domain).