Modeling the influence of local network activity on neuron spiking responses in primary visual cortex

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The de facto standard for modeling neural responses to visual stimuli is a cascade of linear and point-wise nonlinear processing stages. Despite the success of these models in accounting for part of the single neuron firing rate, they generalize poorly and are less successful at predicting neuronal responses to naturalistic stimuli [1]. Notwithstanding the difficulty of fitting the many parameters of these models, other limitations are more fundamental: they are only designed to capture responses that are time-locked to the stimulus; they ignore sources of trial-to-trial variability, regarding them as noise; and they do not explicitly model interactions between neurons. Yet the activity of single neurons is modulated by not only the stimulus, but also ongoing local network dynamics, even in primary sensory cortices.

Here we seek to improve the performance of predictive models by explicitly including the activity of other neurons, including meso-scale activity as reflected in the local field potential (LFP), and by fitting single-trial spike trains rather than trial-averaged rates. Using the generalized linear model (GLM) framework [2], the standard feed-forward spatiotemporal receptive field, spiking history, activities of other local neurons, and the influence of the network activity (LFP) can be included as factors modulating the spiking probability. Since single neuron spiking activity is strongly phase-locked to the band-passed LFP in various frequencies [3], we included here a factor of the form:

\[
\lambda(t|\alpha, \beta) = \exp\left\{ \sum_i \alpha_i \cos(\phi_i(t)) + \beta_i \sin(\phi_i(t)) \right\}
\]

that multiplies the spiking probability depending on the phases \(\phi_i\) of the LFP at frequencies \(f_i\). We fit the parameters \(\alpha_i\) and \(\beta_i\) to data recorded with high-density silicon electrode arrays comprising simultaneous recordings of 100+ neurons spanning all cortical layers in anesthetized cat primary visual cortex [4]. Brief 5s white noise and natural scene movie segments were presented 25-75 times (50Hz frame rate, 200Hz refresh). Complex Morlet wavelets were used to obtain an instantaneous measure of LFP phase in frequency bands from 1-150Hz.

The addition of the LFP component (1) to the model significantly improved the explained variance (\(r^2\)) of the average firing rate. More importantly, the model captured the spike timing structure on individual trials, as measured by an increase in the likelihood estimate. These encouraging preliminary results suggest that this type of modeling will give a fuller and more quantitative understanding of the relations between single neurons and network-level dynamics in the primary visual cortex.