Impact of intrinsic biophysical diversity on the activity of spiking neurons

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We study the effect of intrinsic heterogeneity on the activity of a population of leaky integrate and fire neurons. By rescaling the dynamical equation, we derive mathematical relations between multiple neuronal parameters and a fluctuating input noise. To this end, common input to heterogeneous neurons is conceived as an identical noise with neuron specific mean and variance. As a consequence, the neuronal output rates can differ considerably, and their relative spike timing becomes desynchronized. This theory can quantitatively explain several recent experimental findings.

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I. INTRODUCTION

In statistical physics, it is often assumed that individuals are intrinsically identical. In neuroscience also, identical parameters are typically assumed for all neurons in the study of neuronal population activity and correlation transmission. Real neurons, though, even if they are of the same type and located in the same brain area, exhibit intrinsic differences. Their morphologies and the intracellular concentrations of ions, to name just two examples, can differ widely, although in principle they have been generated by the same mechanisms [1]. As a consequence, neuronal spike patterns can differ although neurons receive identical inputs [2,3]. Recently, in vitro intracellular recordings of isolated mitral cells in the mouse olfactory bulb were conducted while they responded to identical input [3] [Fig. 1(a)]. The neurons displayed diverse output firing rates and pairwise correlations. Specifically, the spike correlation coefficient obtained with a 1 ms observation window covered with the rate difference of the neuron pairs: small differences resulted in a wide range of different spike correlations, but large differences led always to small spike correlation.

In homogeneous network models, additional independent Gaussian white noises or independent Poisson spikes are very often added to every constituent neuronal neuron to account for their diverse spike timing. In real brain networks, not only the spike timing but also the spiking rate of neurons differ due to their intrinsic biophysical diversity. Therefore, it is of great interest to understand how the biophysical heterogeneity of a neuronal population contributes to neural coding and information processing in neuronal networks. Research work has been conducted on the coding properties [4,5] and synchronous responses [6-8] in a network of heterogeneous neurons. In many cases, neuronal heterogeneity was implemented simply by replacing one or more fixed neuronal parameters, such as the offset current [6,7], the spiking threshold [5], or the synaptic conductance [4], by a Gaussian- or uniformly distributed random variable.

Here we investigated more fundamental questions, using both theoretical analysis and simulations: how neuronal heterogeneity can be represented appropriately in theory and how it can affect the neuronal dynamics and the spiking statistics in a population of simple leaky integrate-and-fire (LIF) neurons. The limitations of the existing approaches are addressed first. Then we suggest a more general scheme to implement biophysical diversity when either rate or correlation is of interest. By rescaling the dynamical equation, we derive mathematical relations between multiple neuronal parameters and the input noise. The main impact of common input to heterogeneous neurons on rate and correlation can be realized by an identical (frozen) noise current injection with different values of mean and variance, whereas the complete effect is captured by additionally drawing distributed values of the membrane time constant and the refractory period. In this scheme, the rate difference of heterogeneous LIF neurons can be treated analytically. As for correlation, we utilize alternative correlation measures to illustrate that spikes from heterogeneous neurons may be desynchronized by several milliseconds, thus escaping detection by a 1 ms observation window.

II. MODEL

We consider a population of isolated leaky integrate-and-fire (LIF) neurons, each of which has its membrane potential $V(t)$ governed by

$$\tau_m \frac{d}{dt}V(t) = -V(t) + RI(t),$$

where the input synaptic current

$$RI(t) = \tau_m J_E \sum_j \delta(t - t_j) - \tau_m J_I \sum_k \delta(t - t_k).$$

$\tau_m = RC$ is the membrane time constant, $R$ and $C$ are the membrane resistance and capacitance, respectively. $J_E$ ($J_I$) is the amplitude of an excitatory (inhibitory) postsynaptic potential, whereas $t_j$ ($t_k$) represents the time of the $j$th ($k$th) excitatory (inhibitory) input spike. When $V(t)$ passes the threshold $\theta$, a spike is elicited, $V(t)$ is reset to $V_0$ and a pause for synaptic integration $\tau_s$ is imposed to mimic the refractory period. In the high-input regime, the sum of synaptic inputs to a neuron can be approximated by a fluctuating input noise [9,10]

$$I(t) = \tau_m [\mu + \sigma \eta(t)],$$

where

$$\mu = J_E v_E - J_I v_I,$$  \hspace{1cm}  (4)

$$\sigma = \sqrt{J_E^2 v_E + J_I^2 v_I}.$$  \hspace{1cm}  (5)

$\eta(t)$ is a white noise random process such that $\langle \eta(t) \eta(t') \rangle = \delta(t - t')$, $v_E$ ($v_I$) is the firing rate of the excitatory (inhibitory) input.