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High discharge variability in neurons driven by current noise

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Abstract

Cortical neurons in vivo show a highly irregular spontaneous discharge activity, characterized by a gamma statistics and coefficient of variation around unity. Modelling studies showed that this irregularity is a consequence of the high-conductance state caused by the ongoing activity in the cortical network. Here, we investigate to which extent this high discharge variability can be reproduced in vitro using current noise injection. In agreement with numerical studies, we found that equalizing the time constant of the noisy input with the membrane time constant may lead to an irregular discharge activity which, however, departs from a gamma statistics.

Keywords: Cerebral cortex; Irregularity; Dynamic-clamp; Gamma process

1. Introduction

The spontaneous activity of cortical neurons recorded in vivo, as well as the response to a sensory stimulus, is highly irregular [1,10,11]. This irregularity is quantified by a coefficient of variation (C_V), defined as the ratio between the standard deviation and the mean interspike interval (ISI), close to unity. Another property of spontaneous discharge activity in vivo is that the distribution of ISIs

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follows gamma statistics, i.e. it is both exponentially distributed for large intervals and with refractory period for small intervals, as well as independent.

In computational studies of reconstructed cortical neurons it was shown [8] that, for spontaneous rates below 50 Hz, a high discharge variability following gamma statistics was always paralleled with a high-conductance state [3]. Moreover, using effective models of synaptic noise, either in the form of stochastic conductances or stochastic currents described by random-walk processes [2,7], it was found that current noise, in general, leads to a lower C_V compared to conductance noise. However, under specific condition, such as for a large time constant of the stochastic current, the discharge can be highly irregular (C_V close to 1) but deviates from the gamma distribution.

Here, we investigate to which extent current noise can be used to reproduce the irregular spontaneous discharge of cortical neurons (e.g. [5]). We recorded from regular spiking cortical neurons in vitro subject to current and conductance noise, and compared the C_V in both conditions. The discharge variability depended on the noise time constants (see also [12]) and, for current noise, high C_V values were always paralleled by a non-gamma statistics of the ISIs.

2. Methods

Intracellular recordings in vitro were performed on slices from ferret occipital cortex. To obtain spontaneous activity, current or conductance noise based on random-walk processes [2,7] was injected into the cell. Injection of conductance noise was performed using the dynamic-clamp technique utilizing a modified version of the NEURON simulation environment ([4]; Le Masson, unpublished). To investigate if the spike trains followed gamma statistics, the ISI histograms (ISIH) were fitted by a gamma distribution $\rho_{\text{ISI}}(T) = ar(rT)^q \text{e}^{-rT}/q!$, where a, r, and q are parameters and T denotes the lag time. The fitting procedure consisted in finding the parameter set which minimizes the root-mean-square error. In addition, autocorrelograms of the output spike trains were constructed to evaluate the degree of independence of the ISIs.

Two simplified models of the time-dependent membrane current due to synaptic noise $I_{\text{syn}}(t)$ were used: The first was a fluctuating conductance model [2], in which $I_{\text{syn}}(t)$ was decomposed into two time-dependent conductances (excitatory $g_{\text{e}}(t)$ and inhibitory $g_{\text{i}}(t)$, with mean g_{e0}, g_{i0}, standard deviation σ_{e}, σ_{i} and time constant τ_{e}, τ_{i}, respectively), each described by an Ornstein–Uhlenbeck (OU) stochastic process. The second model used was a fluctuating current model, where $I_{\text{syn}}(t)$ was directly described by a one-variable OU process with mean I_0, standard deviation σ_I and time constant τ_I.

3. Results

Intracellular recordings were obtained from layer V regular spiking pyramidal cells in the occipital cortical regions. In order to investigate the discharge activity in