Cortical neurons receive signals from thousands of other neurons. The statistical properties of the input spike trains substantially shape the output response properties of each neuron. Experimental and theoretical investigations have mostly focused on the second order statistical features of the input spike trains (mean firing rates and pairwise correlations). Little is known of how higher order correlations affect the integration and firing behavior of a cell independently of the second order statistics. To address this issue, we simulated the dynamics of a population of 5000 neurons, controlling both their second order and higher-order correlation properties to reflect physiological data. We then used these ensemble dynamics as the input stage to morphologically reconstructed cortical cells (layer 5 pyramidal, layer 4 spiny stellate cell), and to an integrate and fire neuron. Our results show that changes done solely to the higher-order correlation properties of the network’s dynamics significantly affect the response properties of a target neuron, both in terms of output rate and spike timing. Moreover, the neuronal morphology and voltage dependent mechanisms of the target neuron considerably modulate the quantitative aspects of these effects. Finally, we show how these results affect sparseness of neuronal representations, tuning properties, and feature selectivity of cortical cells.

**Keywords**  Correlations · Unitary events · Single-cell model · Sparseness · Neuronal selectivity

**Introduction**

The statistical properties of the inputs to a target neuron have a great impact on its response properties, such as the firing rate, spike timing variability, and reliability (Salinas and Sejnowski 2001). Nevertheless, the statistical features of the inputs on a millisecond time scale are currently not known. Higher-order correlation events (also called *unitary events*) define time epochs in the activity of an ensemble of cells, characterized by a conspicuous quasi-synchronous spiking of a large fraction of neurons (Grün et al. 2001; Abeles 1991; Bothé et al. 2000). The large majority of experimental and modeling studies are classically concerned with second order correlation properties of the dynamics (firing rates, coefficient of variation – CV, and pairwise correlations), neglecting the variability of the higher-order correlation terms (Salinas and Sejnowski 2000; Bernander et al. 1994; Feng and Brown 2000). Here we use a computational approach to show that cortical neurons are extremely sensitive detectors of the higher-order correlation properties of
their inputs, thus suggesting that unitary events are deeply involved in neuronal computation and in the mechanisms used by the neurons to encode and transmit information.

To address the question of the impact of higher-order correlation event on the dynamics of cortical neurons, we used the following quantitative approach: we generated an ensemble of spike trains mimicking the dynamics of a large group of neurons. A key feature of the algorithm is the possibility to produce changes in the structure of the higher-order correlation events, while keeping firing rates, CV, and pairwise correlations fixed. We then introduced detailed compartmental models of a cortical Layer 5 pyramidal neuron, a Layer 4 spiny stellate cell and a single compartment, conductance based model of an integrate and fire neuron. The effects of the spike trains were tested on these modeled cells. This allowed us to selectively evaluate the impact of unitary events on the output response properties of the modeled neurons, excluding possible contributions due to changes in the second order correlation properties.

We performed analyses in the time and frequency domain, in the supra- as well as in the sub-threshold domain. Significant changes are observed in each of these scenarios.

In a sequence of controls aimed at studying the scope of the results with respect to modeling parameters, we modified the neuronal morphologies and voltage dependent mechanisms. We showed that the qualitative features of the results are robust for a wide choice of simulation parameters. Moreover, quantitative and qualitative differences emerged whether or not the neuronal morphology was explicitly implemented.

Finally, we highlighted effects of unitary events on population sparseness (Willmore and Tolhurst 2001) and effects on orientation selectivity and tuning properties of single neurons.

**Method**

In the following section we describe the algorithm used to selectively manipulate the higher-order correlation properties of the network dynamics, while keeping the second order parameters constant, i.e. the mean firing rate, the coefficient of variation in the single-cell spiking activity, and pairwise correlation strength between any two given spike trains (see next section for the mathematical definitions of these quantities). We did not use a formal analytical approach. Instead, we created a numerical algorithm, which is based on a probabilistic method.

**Description of the algorithm**

The goal of the algorithm is to produce a large ensemble of spike trains, more specifically produce an ensemble of 5000 spike trains, lasting $T_s$ seconds each ($T_s = 10$ s). Spikes are not assigned randomly, so that temporal correlations between the spikes are introduced. For the sake of clarity, we will use the schematic representation of Fig. 1a to exemplify the concepts describing the algorithm.

- Within the overall time window of analysis $T$, time epochs ($E_1, E_6$, top panel) are pre-selected for all the spike trains in the ensemble, during which the correlated spiking activity can occur. The time window is subdivided in small time bins of width $\Delta T_{bin} = 0.1$ ms, which represents the time resolution of the system. The frequency of the time epochs ($f_E = N_E/T$, with $N_E$ the total number of epochs in the interval $T$) can be 84, 133, and 153 Hz (see also the Result section); for simplicity,