A simple and fast method to represent rates and temporal patterns in multielectrode recordings*

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Abstract

Increasing evidence suggests that the brain utilizes distributed codes that can be only analyzed by simultaneously recording the activity of multiple neurons. However the methods for data analysis that could identify functional neuronal interactions within these high dimensional data sets are generally lagging behind the development of the tools used to acquire this data. This paper introduces a new representation of raster plots of neural ensemble recordings, in which instead of plotting single spikes, we have plotted spikes conditioned by the presence of other spikes in its temporal vicinity. These results suggest that several consecutive spikes from different neurons within an extended time window may encode behaviourally relevant information. This information can be best detected when temporally structured activity between neurons is taken into account.

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An emerging view in neuroscience is that sensory and motor information is processed in a parallel fashion by populations of neurons working in concert. Encouraged by this progress many laboratories are investing considerable effort into the development of recording techniques and spike-sorting algorithms that permit simultaneous recording of the activity of multiple neurons. However the development of tools used to analyze this multi-neuronal activity is generally lagging behind the development of the tools used to acquire this data. In this context, a fundamental and long-standing question is the type of neural codes used by the population of neurons to represent information in trains of action potentials [1, 2]. The firing rate of spike trains is a candidate for such a neural code [3], however it is possible that spike timing rather than firing rates plays a significant role in this task.

A key factor in distinguishing among these theories is the temporal precision of individual action potentials. Thus, it is important to measure this precision and to develop new methods to describe population spike trains. Taking into account the above considerations, we have developed a simple representation of the spiking dynamics in multi-electrode recordings. As we shall explain below, the events we consider are conditioned spikes times, where the condition we impose is the presence of other spike in its temporal vicinity.

Experiments were performed on isolated rabbit retinae, which were superfused with AMES medium during the experimental course. Extracellular multi electrode recording was done as previously described in [4]. Periodic stimuli consisted of a random generated sequence of grey flashes with different intensities and inter-stimulus times.

Figure 1 shows an example of simultaneously recorded responses to fifteen identical and consecutive flashes of the same intensity. For each electrode close inspection of the firing patterns showed some degree of variability, introducing uncertainty in the code. Thus it seems very unlikely that the features of the visual stimulus can be derived exclusively from the activity of single ganglion cells.

First of all, a note must be made regarding the concept of velocity or firing rate. The rate is not a well defined property of a sequence of events [1, 5] and, roughly speaking, we can consider two main definitions. The first one is the original Adrian's concept of rate, as the number of spikes in a (usually large) time interval. On the other side, one can define the time dependent firing rate by averaging over many realizations of the same experiment. Much more elaborate concepts has been used also. We shall consider here as the firing rate the inverse of the corresponding inter-spike-interval, that is, instantaneous firing rate. In

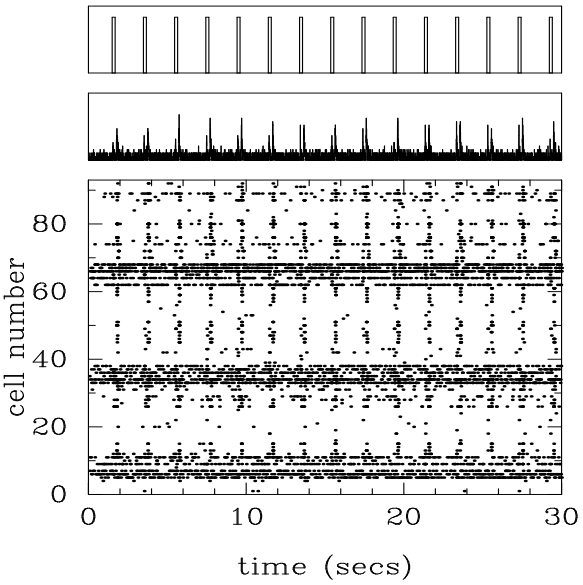

FIG. 1: Raster plot of a simultaneous recording from retina rabbit cells under periodic stimulation. The upper panel shows graphically the timing and stimuli intensity. the middle panel shows the population response, summed up individual responses in bins of 5 mS. The lowe panel shows ganglion cells responses. Each dot represents a spike

this way, no binning of the data is introduce, beyond that of the resolution given by the acquisition system.

Given an experimental record from a single neuron, we call t_i the time of the i spike. In the case of multi-electrodes registers, from different simultaneous record, we call t_i^α the time of the spike i from the α neuron. In this way we have a multivariate, discrete, time series with the information about the spiking dynamics of the neurons. We define new events using the above information, and the times of these new events are such that:

$$\tau_i^\alpha = t_i^\alpha \iff T_1 < t_i^\alpha - t_{i-1}^\alpha < T_2 \;\; ; \; i = 2, m_\alpha \tag{1}$$

where m_α is the number of spikes the cell α has fired in the total time considered, and we extend this definition to the others cells β, γ, and so on. The above procedure select discrete firing events with firing rates in the range $f_r \pm \Delta f_r$, with $f_r = (1/T_1 + 1/T_2)/2$ and $\Delta f_r = (1/T_1 - 1/T_2)/2$. Defining events in this way allow us to window the behavior of the neurons through different firing rates values.

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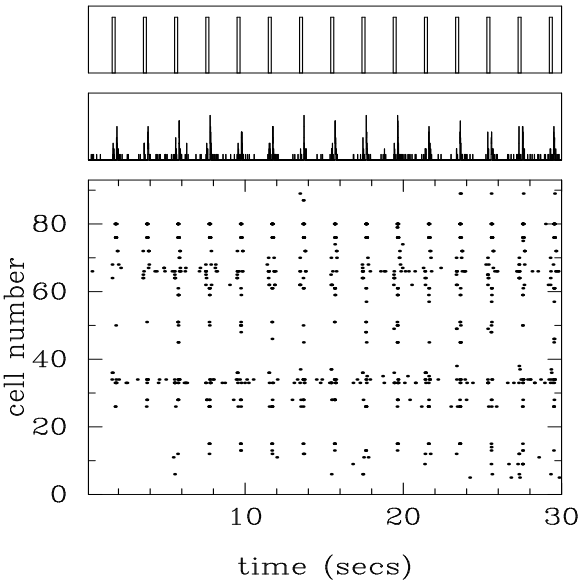

FIG. 2: Conditioned spikes: Raster plot of a simultaneous recording from retina rabbit cells under periodic stimulation, where the dots now represent spikes consistent with firing rates in between 50 and 500 Hz. The upper panel shows graphically the timing and stimuli intensity. the middle panel shows the event population response, summed up individual responses in bins of 5 mS. The lowe panel shows ganglion cells responses. Each dot represents an event

ganglion cells through different firing rates values. For example, in Figure 2 we can see the events corresponding to Figure 1, for a window of 50-500 spikes/seconds (T1 = 2 mS and T2 = 20 mS). Each dot in the figure now represent a spike, and its corresponding time as in Figure 1, but with the condition that there must be at least other spike temporally close to it. We shall call events to this conditioned spikes, in order to differentiate them from the single spikes. It is clear that in the case of n spikes separated between them by less than the temporal window used, we shall plot just n-1 spikes, the first one is missing.cells.

We now compare Figure 1 against Figure 2, that is spikes against events. In the case of Figure 1, although most of the cells follow the periodic stimulation very closely, there are several cells whose responses are not so clear (some of them show a very high firing rate). In Figure 2 however, it is readly seen the periodic response of all the cells involved, even those cells with high firing rates. Indeed, when these spikes are plotted taking into account the firing rate events in which they are immersed, the response seems to be noise reduced. Obviously, the number of firing cells is reduced using this kind of representation, because not of all the cells are firing beyond certain threshold.

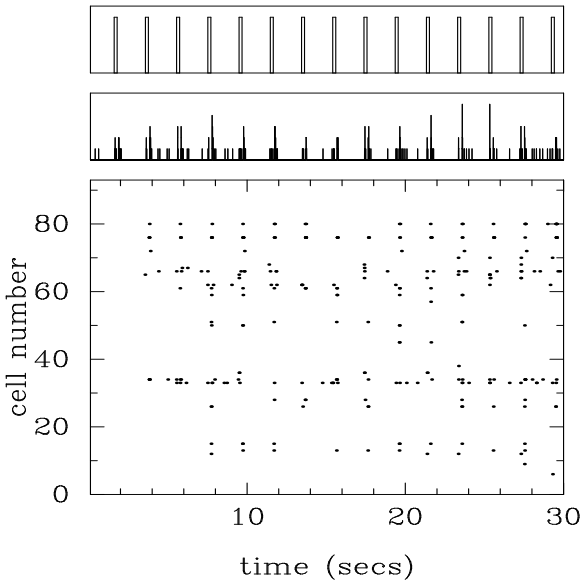

FIG. 3: Conditioned spikes: Raster plot of a simultaneous recording from retina rabbit cells under periodic stimulation, where the dots now represent spikes consistent with firing rates in between 1000 and 2500 Hz. The upper panel shows graphically the timing and stimuli intensity. the middle panel shows the event population response, summed up individual responses in bins of 5 mS. The lowe panel shows ganglion cells responses. Each dot represents an event

The stochastic-like response displayed in Figure 1 is drastically reduced when the instantaneous firing rate are taking into account. This is obviously derived from the Adrian's law. It is clearly seen that the biggest part of the responses are highly correlated with the stimuli. Population analysis, as displayed in the middle panel of both figures also shows the effect of noise reduction in this kind of analysis. However, there remain some events in Figure 2 that do not seems to be causally connected with the stimulus imposed. In this way, the stochastic behaviur of the cells response is still present, although to a less extent.

In Figure 3 we have made the same representation as before, but windowing the cells respones through a firing rates in the range 100 Hz $< f_r <$ 250 Hz.

We have introduced a new representation of raster plots of neural ensemble recordings, in which instead of plotting single spikes, we have plotted spikes conditioned by the presence of other spikes in its temporal vicinity. The method is mainly exploratory, but powerful enough to provide information about the stimulus contained in the temporal pattern of the spike sequence. Furthermore it allows an appropriate mathematical and statistical analysis of multineuronal data.

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