Information processing in a pyramidal-type neuron

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Abstract

A natural stimulus for many cortical neurons is a sum of a large number of unitary excitatory postsynaptic potentials (EPSP) slightly dispersed in time. We use numerical solution of the Hodgkin and Huxley (H-H) equations combined with the Monte Carlo algorithm to find how does the triggering ability of the compound stimulus depend on the relative timing of the EPSPs it comprises. The dependences found allows us to formulate a threshold-type principle with respect to temporal coherence of the unitary signals within the compound stimulus. The binding problem, the role of inhibition in the context of binding, a kind of a short term memory are discussed at the level of single neuron.

1 Introduction

The voltage-threshold principle [1] is widely accepted as criterion for a neuron triggering under external stimuli. Its adequacy is proven for step-like stimuli experimentally and theoretically [2]. On the other hand, a natural stimulus for a cortical pyramidal-type neuron comprises up to several thousands EPSPs [3], and has a gradual time course. The applicability of the voltage threshold principle for this kind of stimuli is under question [4-6]. At the same time, it is suggested that exact timing of spikes in a neuronal assembly is essential for binding, or feature linking during processing of visual [7-9], auditory [10], or complex [11] sensory information. A definite timing of spikes

results in a definite relative timing of EPSPs in a secondary neuron. Our purpose is to establish how does the ability to cause a spike depend on a relative timing of EPSPs within a compound stimulus.

2 Methods

The compound stimulus is taken in the form

(1) $$CompEPSP(t) = \sum_{i=1}^{1000} EPSP(t - t_i),$$

where $EPSP(t)$ is the unitary EPSP time course; $t_n, (1 \le n \le 1000)$ are the random numbers within a fixed time window. We use the H-H set of equations [2] combined with the Monte Carlo algorithm to calculate numerically the dependence of firing probability on the window width, W, if the stimulus (1) is applied to a neuron [6]. A constant potassium conductance is added to the first H-H equation to account for the role of inhibition.

3 Results

Let us denote the degree of temporal coherence between the unitary inputs in the stimulus (1) by the inverse window width: $TC = 1/W$. The obtained dependences on TC of the firing probability are shown in Fig.1. The four curves are calculated for inhibition potentials 0.0, 1.3, 3.8, 7.6 mV respectively from the left to the right . The step-like pattern suggests to a threshold-type principle.

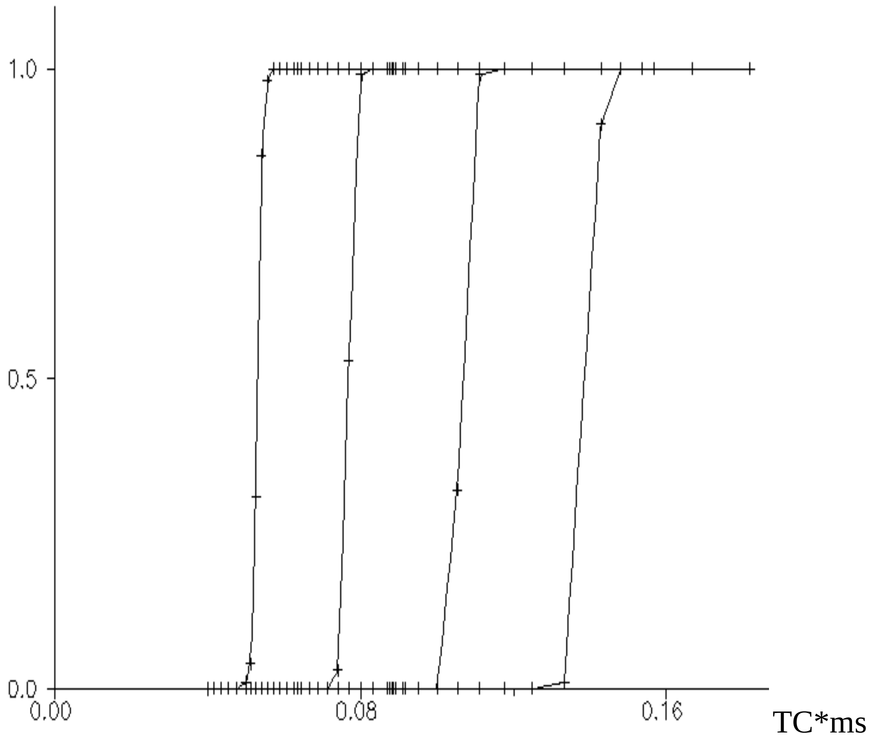

Fig. 1: Probability of neuron triggering vs the temporal coherence between the inputs

4 Conclusions and Discussion

The results obtained lead to the following conclusions:

1. A compound stimulus will trigger a neuron if and only if the degree of temporal coherence between the EPSPs within it is above a definite threshold. In other words, a neuron in natural conditions operates as time coherence discriminator.
2. The degree of temporal coherence necessary for firing can be properly adjusted by means of inhibition.

The above conclusions allow one to offer the following account of the information processing in a single neuron: Synaptic inputs are considered as the inputs from some sensors, an initial segment of axon as the output to one or more effectors. The neuron receives signals into its inputs as signs of various events in the external region. A signal to the effectors has to be sent only if a definite compound event occurs. A decision that the required event has happened is made in the soma, the axonal hillock region, based on the degree of temporal coherence between the inputs (see Fig.2).

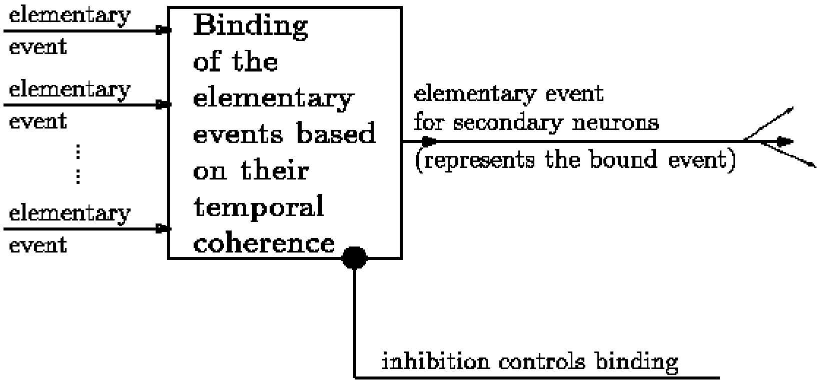

Fig. 2: Information processing scheme. The output spike may be treated as abstract representation of the compound event represented by input synaptic signals

In other words, the neuron converts a suitable set of elementary events represented by the set of synaptic inputs into a single event represented by the action potential in the axon. In this sense we say that binding appears as early as at the single neuron level, and inhibition effectively controls the conditions necessary for this kind of binding.

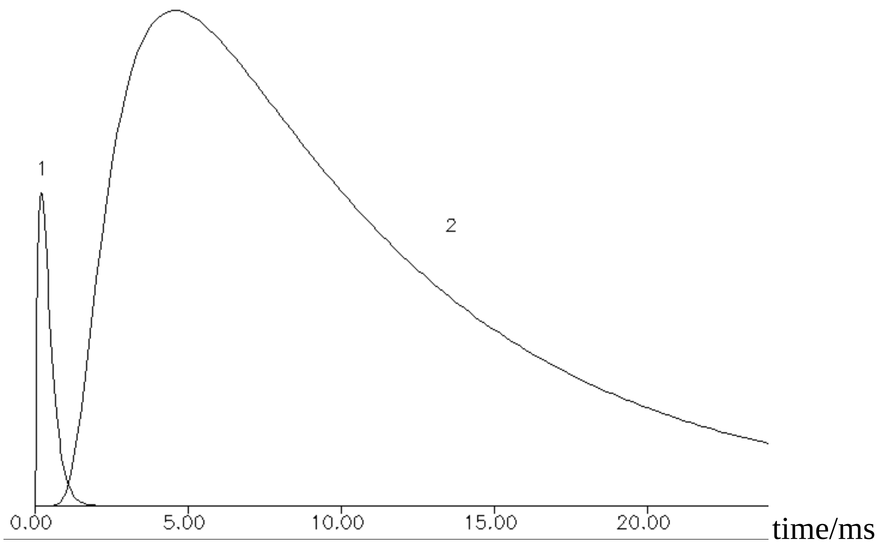

Fig. 3: Synaptic current (1) and excitatory postsynaptic potential (2) time courses. The current maximal value is equal to 400 nA, the potential maximal value is 0.058 mV

In this context, the quick process of synaptic transmission, which is characterized by the postsynaptic current (Fig.3), may be treated as a signal from sensor. The slow transient process characterized by the uEPSP, may be treated as an elementary short term memory mechanism. It is the slowness that makes the binding possible, because due to it the signals about present and recent past events are simultaneously existing in the neuron.

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