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A Proposed Mechanism for Multiplication of Neural Signals

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Abstract

The probability of the joint occurrence of two statistically independent events is the product of the probabilities of the individual events. This fact is used to show that a neuron which detects coincident arrivals of spikes from two input neurons can function as a multiplier, i.e. its average output spike frequency is proportional to the product of the average input spike frequencies. The theoretical analysis is checked in two ways: (a) Computer simulations confirm the derived expressions for the output frequency and show that increasing the jitter in the input spike trains improves the operation of the multiplier by making the output spike train more regular (b) Experimentally recorded spike trains are used to demonstrate that the type and amount of jitter present in real spike trains is adequate for satisfactory operation of the proposed scheme for multiplication. The operating characteristics of the proposed multiplier make it an attractive candidate for the multiplicative mechansim that is involved in the optomotor response of insects.

Introduction

Published experimental evidence points to the existence of multiplicative mechanisms in some nervous systems. Behavioral studies of the optomotor response in the beetle and fly and electrophysiological data on optomotor neurons in the fly infer the existence of neural circuits that perform the operation of multiplication (for reviews, see Reichardt, 1969; Götz, 1972; see also Kirschfeld, 1972; Poggio and Reichardt, 1973; Geiger, 1974; Götz, 1975). However, the mechanism that mediates this multiplication is not yet known. What is the neural basis for this multiplication?

This paper proposes a mechanism by which a single neuron can perform multiplication, by simply detecting coincidences of action potentials (spikes).

A nerve cell that produces spikes encodes the intensity of the signal that it transmits as the average frequency of spikes – the greater the signal intensity, the higher the frequency. Our goal is to describe a scheme by which a neuron C can produce a response which is proportional to the product of the input signals that it receives from two other neurons, A and B. Therefore, the average spike frequency of neuron C must be proportional to the product of the average spike frequencies of A and B.

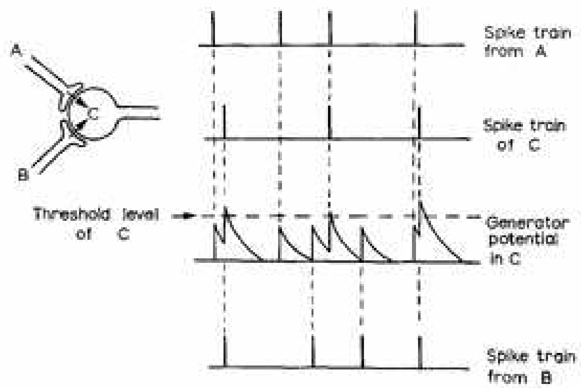

Fig. 1. Illustrating the operation of a neuron as a coincidence detector. Neuron C receives input from neurons A and B through excitatory post-synaptic potentials (EPSP's). Neuron C will operate as a coincidence detector if two conditions are satisfied: (a) Each spike from A or B induces an EPSP in C whose peak amplitude is somewhat lower than the threshold level for initiating a spike in C. This condition ensures that a spike is triggered in C only by two coincident or nearly coincident presynaptic spikes, not by a single spike. (b) The smallest interspike interval in the spike train from A (and similarly from B) is larger than the duration of the EPSP's that it induces in C. This ensures that each spike in C is triggered only by a spike from A *and* a spike from B that are coincident or nearly coincident, and not by temporal summation of the EPSP's induced by the spike train of a single input neuron. This condition places an upper limit on the frequency of each input train for proper operation of the neuron as a coincidence detector (see text)

In the proposed scheme the neuron C produces a spike only if it receives two spikes, one from A and one from B, that are coincident in time or nearly so. Figure 1 describes the conditions under which a neuron can operate in this mode. The requirements are not stringent – neuron C can be "normal" in all respects, except for a restriction on its threshold level and on the duration of its synaptic potentials.

In the following analysis, we use the idea of statistical independence to derive an expression for the spike frequency of C in terms of the spike fre-