High Conductance Dynamics of the Primary Visual Cortex

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It is our pleasure to dedicate this article to Larry Sirovich on the occasion of his 70th birthday. Given Larry’s many contributions to scientific modeling using asymptotic analysis, we believe that the concept of an “emergent separation of time-scales” in cortical processing will be particularly appealing to him.

ABSTRACT This article discusses large synaptic conductance increases, and their consequent separation of time-scales, which can result from cortical activity, together with some implications of these large conductances for cortical processing. The specific setting is the primary visual cortex (Area V1) of the Macaque monkey, as described by a large-scale neuronal network model (McLaughlin, Shapley, Shelley, and Wielaard [2000]), and the comparison of this model’s performance (Shelley, McLaughlin, Shapley, and Wielaard [2002]) with observations from laboratory experiments (Borg-Graham, Monier, and Fregnac [1998]; Hirsch, J.M.Alonso, Reid, and Martinez [1998]; Anderson, Carandini, and Ferster [2000]). In the model, the source of large conductances is traced to inhibitory cortico-cortical synapses, which set a high conductance operating point in which the model cortical layer achieves orientation selectivity, neuronal dynamics and response magnitude, and the linear dependence of simple cells on visual stimuli (e.g. Wielaard, Shelley, Shapley, and McLaughlin [2001]) consistent with experimental observations. In the absence of visual stimulation, the high conductance operating point sets relaxation time-scales at the synaptic time scale (≈ 4 – 5 ms). High contrast visual stimulation produces cortical activity which further reduces this relaxation time scale by a factor of 2, so that it becomes even shorter than synaptic time-scales. While only a factor of 2, this is shown to be sufficient to produce the dynamical consequences of time scale separation, including near instantaneous (with respect to the synaptic time scale) responses of neurons to temporal changes in synaptic drive, with each intracellular membrane potential tracking closely an effective reversal potential composed of the instantaneous synaptic inputs. This
time scale separation, which emerges from cortical activity, permits the use of methods from asymptotic analysis to express the spiking activity of a cell in simplified manner. These asymptotic results suggest how accurate and smoothly graded responses are achieved in the model network. Further, since neurons in this high-conductance state respond quickly, they are also good candidates as coincidence detectors and as burst transmitters.

1 Introduction

Neurons communicate with each other by detecting and responding to voltage spikes in the membrane potentials of other neurons. The dynamics of a neuron's membrane potential is described by the voltage difference across the cell's membrane, and is governed by the conductance of the membrane (the inverse of its electrical resistance). (See, for example Koch [1999].) The value of this conductance is not a static membrane property, but changes with time through synaptic processes which are initiated by impinging voltage spikes from other neurons. Thus, the value of the conductance is influenced by the activity of the neuronal network.

For fixed capacitance $C$ (a cellular property which is static), the value of the conductance $g$ sets a time-scale $\tau_g \equiv C/g$ upon which the neuron responds to synaptic input. Until recently, this time-scale was treated as well