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Calcium window currents, periodic forcing and chaos: understanding single neuron response with a discontinuous one dimensional map

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Thalamocortical (TC) neurons are known to express the low voltage activated, inactivating Ca^{2+} current I_T. The triggering of this current underlies the generation of low threshold Ca^{2+} potentials that may evoke single or bursts of action potentials. Moreover, this current can contribute to an intrinsic slow (< 1 Hz) oscillation whose rhythm is largely determined by the steady state component of I_T and its interaction with a leak current [1]. This steady state, or *window current* as it is so often called, has received relatively little theoretical attention despite its importance in determining the electro-responsiveness and input-output relationship of TC neurons.

In this paper, we introduce an integrate-and-fire spiking neuron model that includes a biophysically realistic model of I_T. We briefly review the sub-threshold bifurcation diagram of this model with constant current injection before moving on to consider its response to periodic forcing. Direct numerical simulations show that as well as the expected mode-locked responses there are regions of parameter space that support chaotic behavior. To reveal the mechanism by which the window current generates a chaotic response to periodic forcing, we consider a piecewise linear caricature of the dynamics for the gating variables in the model of I_T. This model can be analyzed in closed form and is shown to support an unstable set of periodic orbits. Trajectories are repelled from these organizing centers until they reach the threshold for firing. By determining the condition for a *grazing* bifurcation (at the border between a spiking and non-spiking event) we show how knowledge of the unstable periodic orbits (existence and stability) can be combined with the grazing condition to determine an effective one-dimensional map that captures the essentials of the chaotic behavior. This map is discontinuous and has strong similarities with the universal limit mapping in grazing bifurcations derived in the context of impacting mechanical systems [2].

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