What Are Autapses Good for?

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Summary. I develop a simple model of an autaptic neuron and analyse its neurocomputational properties. I show that the model can capture diverse experimental observations and demonstrate how autapses can provide a novel biologically plausible route to chaos in cortical pyramidal cells.

An autapse is a synapse connecting the neuron to itself. Previous anatomical studies suggest that Autapses in excitatory cortical neurons known as pyramidal cells are rare, irrelevant errors in neuronal wiring. However, a recent electrophysiological study challenges this view by showing that autapses are a common phenomenon, specifically in layer 5 pyramidal cells of the prefrontal cortex, that are also functionally relevant to neural computation [1]. Among other findings, Yin and colleagues [1] observed that autapses enhance bursting in pyramidal cells, which may suggest a role in boosting neural information transmission. Furthermore, previous studies on a genus of marine invertebrates called aplysia demonstrate that autapses in aplysia's motor neurons facilitate persistent activity (necessary for memory) in the absence of sufficiently strong input [2], a phenomenon that was not observed in layer 5 pyramidal cells according to Yin and colleagues.

The first aim of this work is to reconcile these disparate experimental observations within a single theoretical framework, namely, dynamical systems theory [3]. I augmented a simple, biophysical neural model with autaptic excitation. Simulations show that, for different parameter choices, the presence of an autapse either enhances bursting, as in layer 5 autaptic prefrontal pyramidal cells (Figure 1, left) or leads to persistent activity in absence of strong external excitation, as in autaptic motor neurons in the aplysia (Figure 1, right). As I will show, the fact these results conform to two different experimental observations is not surprising when taking a dynamical-systems perspective, and it reflects the nonarbitrary choice of parameters, which is based on known biophysical properties of the modelled neuronal structures. This

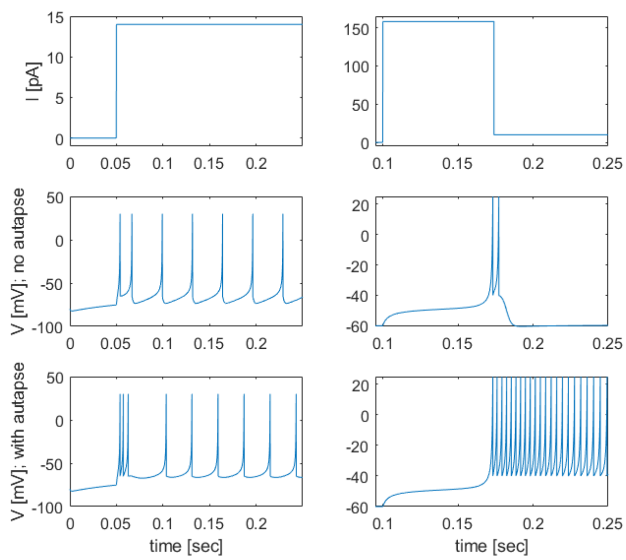

Figure 1. Left, model simulations showing the neuron membrane potential without (middle) and with (bottom) an autpase given layer 5 pyramidal cell biophysical parameters. Without an autapse, the neuron shows regular firing. With an autapse, the neuron shows an initial burst of action potentials (or spikes), in strong agreement with experimental observations in [1]. Right, same as (left) for aplysia motor-neuron parameters, showing persistent activity due to the presence of an autapse in the absence of a strong stimulation current, consistent with experimental observations in [2]. Top panels show the stimulation current in each case.

suggests that this autaptic neuron model can support diverse modes of operation that correspond to different neuro-computational properties of functionally specific cell types.

The second aim is to present a novel, biologically plausible route to chaos in single neuron models. While previous studies discovered parameter regimes within which single neuron models act as chaotic dynamical systems [4], these parameter regimes were outside the ranges that can be observed naturally. Chaos in single neurons remained therefore a subject of mathematical curiosity, rather than a biologically plausible phenomenon. On the other hand, it is very easy to induce chaos in a dynamical system by incorporating delays. Indeed, chaos [5,6] and delays [7,8] are two important ingredients for richer neural dynamics that can support complex computations. Interestingly, staying within a biologically plausible layer 5 parameters in the current model, adding a delay to the autaptic current as it arrives to the soma, and applying a strong stimulation current give rise to chaos (Figure 2). This suggests delayed autaptic pyramidal cells may provide another source for neural variability, expanding the dynamic range of these neurons and allowing for complex neural and neuro-inspired computations. This opens the door for further studies investigating the computational properties of spiking neural networks with autaptic connections and for future development of neuromorphic hardware that incorporates delayed autapses into its architecture.

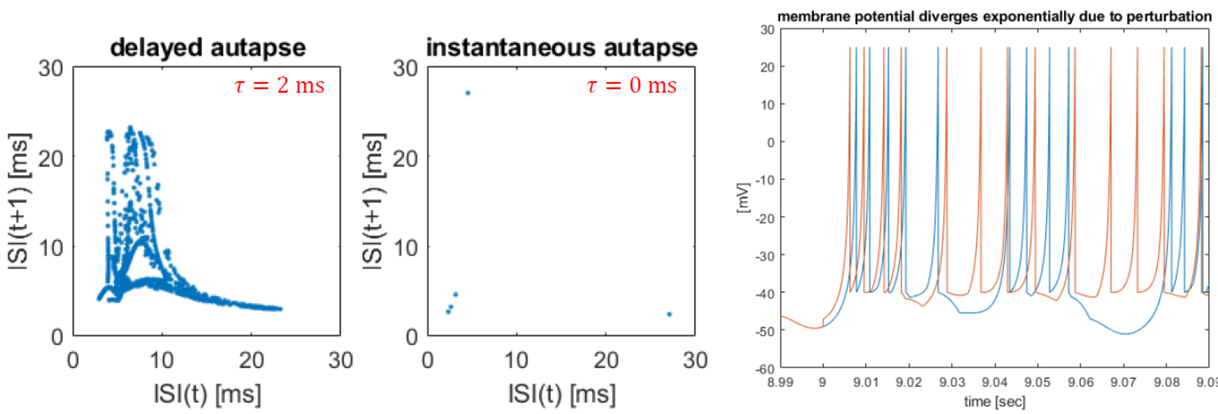

Figure 2. Chaotic first return map (comparing successive inter-spike intervals, or ISIs) for a delayed autaptic current (left), compared to period-5 oscillation for instantaneous autaptic current (middle). Right, a delayed autapse shows high sensitivity to initial conditions, a sign of chaos: perturbing the membrane potential by 2 millivolts resulted in an exponential divergence in membrane potential trajectory and a completely different spiking behaviour.

References

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