Stabilizing Activity and Enhancing Representational Richness through Dendritic Delays in Self-Organizing Recurrent Neural Networks

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Neural systems must coordinate activity across populations while avoiding excessive synchronization, which can collapse dynamics into low-dimensional, stereotyped patterns. At the same time, useful computation in recurrent networks relies on maintaining rich, high-dimensional activity that supports flexible representations of temporal structure [1].
Self-Organizing Recurrent Neural Networks (SORN) offer a biologically inspired framework for studying these dynamics, incorporating mechanisms such as spike-timing-dependent plasticity, synaptic normalization, and intrinsic plasticity to autonomously regulate network activity [2]. However, these models typically assume instantaneous signal propagation and do not account for temporal delays present in biological neurons. Biological neurons, in contrast, are not simple point units [3]. Most synaptic inputs arrive on dendrites, which are extended branching structures that introduce temporally distributed integration of incoming signals. As a result, inputs are not integrated instantaneously, but arrive at the soma with varying delays depending on dendritic location and propagation dynamics. This suggests that temporal dispersion of inputs is a key computational feature.
In this work, we introduce a dendritic-inspired extension of SORN in which recurrent inputs are integrated through multiple delayed pathways.
To quantify the effects of delayed integration, we analyze the dynamics and stability of population activity and memory. In particular, we assess the learning dynamics during training, the dimensionality of population activity and the retention of past inputs using decoding-based memory measures. In addition, we test network stability through targeted perturbations of neural activity, measuring the recovery dynamics and sensitivity of the network to disruptions. We evaluate these properties across different stimulus regimes, including structured periodic and stochastic sequences with varying temporal dependencies.
Our results show that delayed recurrent integration reduces transient synchronization during early training and leads to faster stabilization of network activity. At the same time, delays increase the dimensionality of population activity, indicating richer and more distributed representations. Memory analyses further reveal that delayed integration selectively enhances the retention of structured temporal information, particularly for inputs with higher-order temporal dependencies and depending on ongoing intrinsic plasticity. Perturbation experiments demonstrate that networks with delayed integration recover more rapidly from disruptions and exhibit reduced sensitivity to perturbations, indicating enhanced dynamical stability.
These findings demonstrate that dendritic-inspired delays provide a simple mechanism to stabilize recurrent dynamics while preserving high-dimensional activity, thereby extending the temporal processing capabilities of self-organizing recurrent networks.

[1] B. Del Papa et al., PLoS ONE, 12(5), e0178683, 2017.

[2] A. Lazar et al., Front. Comput. Neurosci., 3, 23, 2009.

[3] M. Häusser, B. Mel, Curr Opin Neurobiol., 13(3), 372-383, 2003.