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Properties of synaptic plasticity rules implementing actor-critic temporal-difference learning

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There is considerable interest in establishing a link between system-level learning and synaptic plasticity. In a previous study we presented a specific set of biologically plausible synaptic plasticity rules implementing temporal-difference (TD) learning in a spiking neuronal network inspired by the actor-critic architecture. We showed the equivalence between the plasticity rules and the traditional discrete-time TD(0) algorithm and demonstrated that the network learns a complex task with a similar speed to its discrete time counterpart and attains the same equilibrium performance. However, the set of learning rules represents only one possible way in which actor-critic TD learning could be implemented in the brain, and so the model has only limited predictive power for experimental work.

Here, we extract properties of synaptic plasticity rules that suffice to implement actor-critic TD(0) learning, under the assumption that states are represented by elevated rates in disjunct sets of neurons. On this basis we define generalized classes of continuous time synaptic plasticity rules that implement value function and policy updates. The main property is that the amount and sign of the weight update depends on a characteristic change in the activity of the critic module combined with a global reward signal. We present concrete examples belonging to the defined class and demonstrate that they are able to solve a non-trivial task. We further analyze to what extent the defined class of plasticity rules are compatible with experimental findings of synaptic plasticity .

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Integration of anatomical and physiological connectivity data sets for layered cortical network models

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The specific connectivity of the local cortical network provides the structural basis for the function of the information-processing unit usually referred to as cortical column, cortical module or canonical microcircuit. We investigate in large-scale simulations the dynamical implications of layer-specific connectivity compatible with experimental data. However, the existing data sets are still diverse in their results as in their methodology ranging from electrophysiology to purely anatomical methods. The integration of the different data sets into a consistent model again advances the interpretation of the data.

Restricting ourselves to pairwise connectivity we use the two most comprehensive and quantitative data sets from the literature. Despite their apparent inconsistency we identify invariant measures that may reflect canonicity in the relationship of intra-layer recurrence and inter-layer projections. The assumption of a gaussian connectivity profile explains the connectivity data while predicting a lateral spread of connections consistent with other studies. This reduces the discrepancies to the specificity in target type selection as typically found for functional connections. Hence, the data sets represent diversity in methodology rather than connectivity. Surmounting this obstacle, we can extract the information required to construct a multi-layered neocortical network model and propose a data set that best summarizes present knowledge.

The dynamical properties induced by layer-specific connectivity are investigated by means of numerical simulations of a local cortical module consisting of 80,000 neurons. We elaborate on the existence and stability of asynchronous irregular activity for stationary and transient thalamo-cortical inputs, respectively. The cortical connectivity alone predicts a distribution of firing rates across layers. Quantification of target type specificity allows us to ascertain its dynamical implications.

We integrate various data sets and find that local connectivity is best described by layers of balanced random networks interconnected with partly target specific projections providing feed-forward and feedback signaling. Our quantitative analysis supplies researchers with the information required for simulations and renders the consistent usage of electrophysiological and anatomical data possible. Simulations of the multi-layered model can now be compared to the observed network activity, linking structure to dynamics.

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On the propagation of firing rate and synchrony in a model of cortical network

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Sensory information in the brain is processed in multiple stages. In this view of information processing, the information needs to be carried from one cortical region or area to the next. A very simple model for this type of processing is a feed forward chain of groups of neurons (FFN), in which each neuron in a given group receives multiple synaptic inputs from neurons in the previous group. FFNs were shown to have different operating modes, where they transmit either firing rates or synchronous volleys of spikes. These findings have been partially confirmed in in vitro experiments. The transmission of information in a FFN, be it rate based or synchrony based, is strongly influenced by background activity. In most studies of isolated FFNs the background was assumed to be independent of the FFN activity. In a more realistic scenario, where the FFN is embedded into a recurrent cortical network, the activity of the FFN interacts with the background activity in the network. In fact, it was shown that embedding non-random structures with a high degree of shared connectivity, such as an FFN, may introduce instabilities in the network dynamics, such that excitation of only a small group of neurons would be sufficient to induce synchronization of the activity of the entire network. Is this instability a generic property of random networks or an artifact of a too simple model? Recent theoretical work has suggested that conductance-based synapses may help stabilizing the dynamics of the network. This suggestion was motivated by the fact that in networks in a high activity regime, post-synaptic-potentials are strongly attenuated due to the high conductance state. Here, we embedded an FFN in a locally-connected random network. We show that by modeling synapses as conductance transients, rather than current sources, it becomes possible to embed and propagate transient synchrony in the FFN, without destabilizing the background network activity. However, the network activity has a strong impact on the conditions under which propagation of activity in the embedded FFN is possible. Global synchrony and high firing rates in the embedding network prohibit the propagation of both synchronous and asynchronous spiking activity. By contrast, asynchronous low rate network states support the propagation of synchronous spiking and asynchronous, albeit only low, firing rates. In either case, spiking activity tends to synchronize as it propagates, rendering the transmission of information only in firing rates problematic. Finally, asynchronous background activity allows us to embed more than one FFN, with the amount of cross-talk depending on the degree of overlap in the FFNs, opening the possibility of computational mechanisms utilizing transient synchrony among the activities in multiple FFNs.

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Comparison of methods to calculate exact spike times in integrate-and-fire neurons with exponential currents

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Discrete-time neuronal network simulation strategies typically constrain spike times to a grid determined by the computational step size. This approach can have the effect of introducing artificial synchrony. However, time-continuous approaches can be computationally demanding, both with respect to calculating future spike times and to event management, particularly for large network sizes. To address this problem, Morrison et al. presented a general method of handling off-grid spiking in combination with exact subthreshold integration in discrete time driven simulations. Within each time step an event-driven environment is emulated to process incoming spikes, whereas the timing of outgoing spikes is based on interpolation. Therefore, the computation step size is a decisive factor for both integration error and simulation time.

An alternative approach for calculating the exact spike times of integrate-and-fire neurons with exponential currents was recently published by Brett. The problem of accurate detection of the first threshold crossing of the membrane potential is converted into finding the largest root of a polynomial. Common numerical means like Descartes' rule and Sturm's theorem are applicable. Although this approach was developed in the context of event-driven simulations, we take advantage of its ability to predict future threshold crossings in the time-driven environment of NEST. We compare the accuracy of the two approaches in single-neuron simulations and the efficiency in a balanced random network of 10,000 neurons. We show that the network simulation time when using the polynomial method depends only weakly on the computational step size, and the single neuron integration error is independent of it. Although the polynomial method attains the maximum precision expected from double numerics for all input rates and computation step sizes, the interpolation method is more efficient for input rates above a critical value. For applications where a lesser degree of precision is acceptable, the interpolation method is more efficient for all input rates.

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