Consequences of realistic network size on the stability of embedded synfire chains

Tom Tetzlaff *, Abigail Morrison, Theo Geisel, Markus Diesmann

Department of Nonlinear Dynamics, Max-Planck-Institut für Strömungsforschung, Göttingen, Germany

Abstract

Cortical activity in vivo is characterized by asynchronous irregular spiking. Simultaneously, precise spike synchronization occurs in relation to the experimental protocol. Theoretical studies focused on two limiting networks: random and feed-forward graphs (synfire chains). Recently, researchers have started to investigate more realistic structures by implanting feed-forward subgraphs into random networks. We successively convert an isolated synfire chain into a completely embedded one, thereby uncovering the components of the embedding scheme determining the stability of the system. At a realistic network size, common-input correlations play a major role. Surprisingly, their impact is reduced by the dynamics of the embedding recurrent network.

Key words: recurrent network, synfire chain, common-input correlation

Summary

In the absence of specific stimuli cortical activity in vivo is characterized by asynchronous irregular firing of the neurons at a low rate. However, the same system exhibits precise spatio-temporal spike patterns in relation to the experimental protocol (e.g. [8], [7]). During the past decade several theoretical studies (e.g. [2], [4]) explored the existence and stability of asynchronous irregular activity states in homogenous random networks of integrate-and-fire neurons. The mechanism of spike synchronization and the generation of spatio-temporal spike patterns in divergent-convergent feed-forward networks ("synfire chains" [1]) is now well understood, too (e.g. [5]). Recent simulation studies pointed out the destabilizing effect of introducing non-random elements into balanced

* Corresponding author. MPI für Strömungsforschung, Postfach 2853, 37018 Göttingen, Germany.
Email address: `tom@chaos.gwdg.de` (Tom Tetzlaff).

random networks. The embedding of feed-forward subnetworks increases the tendency of the whole network to start oscillating in a synchronous manner ([6], [3]). This finding is critical for a concept of the cortical network in which synfire chains serve as the building blocks or substrate for processing. So far, theoretical descriptions of destabilizing mechanisms in synfire chains are documented only for the isolated case, i.e. for synfire chains fed by uncorrelated Poissonian background inputs ([3], [9]). In this context, Aviel et al. [3] focused on the propagation of pairwise correlation along the chain and reported a strong increase of the fixed point correlation if the size w of the feed-forwardly connected neuron pools exceeds a certain critical value. In contrast, in [9] we concluded that the spatial dynamics of firing rates is responsible for the fact that the asynchronous ground state loses its stability. Although we found the results of network simulations being in almost perfect agreement to our theoretical predictions for the isolated chain case, it is not clear whether spatial rate instability can explain the behavior of completely embedded chains.

In the present study, we systematically investigate how the network dynamics is altered by several aspects which were not taken into account in the isolated case:

i) Restricting ourselves to a local volume of cortex in which homogeneous connection probability can be assumed, naturally the embedding network is finite. Consequently, neurons of the same layer in the chain share not only the inputs of their preceding group but also a certain amount of inputs from the background. Hence, the total background inputs of different neurons in a synfire group are correlated, even if the individual inputs are described by Poisson processes.
ii) Due to finite size effects the asynchronous irregular states in unstructured random networks exhibit some small degree of global oscillations, even for network sizes of the order 10^5. Therefore, the assumption that the neurons in the chain are fed by Poisson inputs eventually has to be abandoned. Further, global oscillations embody an additional contribution to the input correlation.
iii) A major postulate of the isolated chain theories was that the activity in the chain does not affect the embedding network. It has to be checked whether the neglect of these feedback connections can be justified or not.

Starting from the isolated case, we successively complete the embedding procedure of the synfire chain in a set of large scale network simulations. Three different simulation paradigms extending the simple scheme of an isolated chain are considered: In a first step (i) we randomly draw the background inputs of the individual neurons in the chain from a large pool of N ($\approx 10^5$) non-interacting Poisson processes. This way, we take the common input correlation caused by finite network size into account, while the Poisson approximation still holds. In the next stage (ii), background inputs are chosen from a large random network of interacting excitatory and inhibitory integrate-and-fire neurons driven by an external source. Feedback from the chain is still absent. The latter is switched on not before the last step (iii), in which the behavior of a completely embedded chain is studied.

To quantify the network dynamics under the four different conditions (isolated case included) we measure the variability (fano factor F) of the population activity as a function of the chains group size w. In all cases we observe a transition from low fano factors at small w to high values at larger w. Our main attention rests on the transition point w_{crit}. As a result we notice that the value of w_{crit} as observed for the finite Poisson background (step i) is considerably smaller than the one we found for the isolated chain, although the pairwise common background input correlation is low (< 0.2). Surprisingly, replacing the Poisson background by a recurrent random network (step ii) causes w_{crit} to return to larger values. The impact of background correlations seems to be compensated by the dynamics of the background network. Adding feedback connections from the chain to the background network (step iii) again can lead to a decrease of w_{crit}. In contrast to the network designs without feedback, here for the first time the length of the embedded chain becomes relevant.

References

[1] M. Abeles, Corticonics: Neural Circuits of the Cerebral Cortex, Cambridge University Press, Cambridge, 1991.

[2] D. J. Amit, N. Brunel, Model of global spontaneous activity and local structured activity during delay periods in the cerebral cortex, Cereb. Cort. 7 (1997) 237–252.

[3] Y. Aviel, E. Pavlov, M. Abeles, D. Horn, Synfire chains in a balanced network, Neurocomputing 44–46 (2002) 285–292.

[4] N. Brunel, Dynamics of sparsely connected networks of excitatory and inhibitory spiking neurons, J. Comput. Neurosci. 8 (2000) 183–208.

[5] M. Diesmann, M.-O. Gewaltig, A. Aertsen, Stable propagation of synchronous spiking in cortical neural networks, Nature 402 (1999) 529–533.

[6] C. Mehring, U. Hehl, M. Kubo, M. Diesmann, A. Aertsen, Activity dynamics and propagation of synchronous spiking in locally connected random networks, (in press), 2003.

[7] Y. Prut, E. Vaadia, H. Bergman, I. Haalman, S. Hamutal, M. Abeles, Spatiotemporal structure of cortical activity: Properties and behavioral relevance, J. Neurophysiol. 79 (1998) 2857–2874.

[8] A. Riehle, S. Grün, M. Diesmann, A. Aertsen, Spike synchronization and rate modulation differentially involved in motor cortical function, Science 278 (1997) 1950–1953.

[9] T. Tetzlaff, T. Geisel, M. Diesmann, The ground state of cortical feed-forward networks, Neurocomputing 44–46 (2002) 673–678.