

STRUCTURAL ASPECTS

Subjecting the directionally heterogeneous network model to a critical examination of its structural features, we identify prevalent patterns of connectivity and relate theoretical and computational results to findings from experiments in the rat's visual cortex.

1.1 INTRODUCTION

Investigation of the brain's connectivity is an ongoing endeavour. Concurrent collaborative efforts like the Human Connectome Project [HCP], the Open Connectome Project [OCP] and the Allen Brain Atlas [ABA], intent on mapping the 'wiring' of the brain, as well as the continued development of experimental techniques and computational resources, demonstrate the great interest in advancing this field.

Research in brain connectivity spreads over the whole scale of the brain; from the mapping of fiber pathways between brain regions at the macroscopic level, to the synaptic connections of individual neurons on the microscale, researchers are trying to identify the links that enable the brain its characteristic cognitive abilities. In the search for structural connections, these links are of anatomical nature. However, statistical dependencies and causal relationships between the distinct computational units in the brain are being researched with equal emphasis (Sporns 2007).

Connectivity in the context of the directionally heterogeneous geometric networks introduced in ??, refers in this chapter to structural links. So far, we have only briefly mentioned that the network's nodes should be interpreted as individual neurons; to allow for a discussion of functional relationships between nodes, we have yet to provide a physical description of a neuron's function. As such, we will here explore the network's structural connectivity, modeling synaptic contacts between axon and dendrites of individual neurons.

Synaptic Connectivity

In the local cortical circuits the anisotropic geometric model was derived from, synaptic connectivity is a major mode of configuration. In those networks, connectivity has been determined to be neither completely random nor exclusively specific [Source]. Recurring patterns of connectivity have been identified by several reports (Sporns and Kötter 2004; Song et al. 2005; Perin, Berger, and Markram 2011).

HUMAN
Connectome
PROJECT
humanconnectome.org

Open Connectome
Project
openconnectome-project.org

ALLEN BRAIN ATLAS
brain-map.org

The impact of this structural specificity discovered in local networks is shown to be significant; while the linking of network structure and network dynamics remains an active field of research, several studies were able to employ computational and theoretical models to establish such a connection. A study by Zhao et al. from 2011, for example, demonstrates how second order connectivity statistics affect a network's propensity to synchronize [Zhao et al. 2011](#). In the same year, Alex Roxin reported on the influence of in- and out-degree distributions on dynamics of neural network [Roxin 2011](#). Later, Pernice et al. were able to link structural connectivity to spike train correlations in neural networks [Pernice2011](#)

Mapping synaptic connectivity in experiments

Experimentally, paired intracellular recordings are used to determine synaptic connectivity in cortical slices. Using two electrodes, one inserted in the cell and one outside the cell, a single intracellular recording allows for measurement of a cell's membrane potential [Brette and Destexhe 2012](#)[Weckstrom 2010](#). Simultaneous recordings from multiple neurons are then able to infer synaptic connectivity by evoking an action potential through current injection in one neuron and observing the change of membrane potential in the other cells [Song et al. 2005](#).

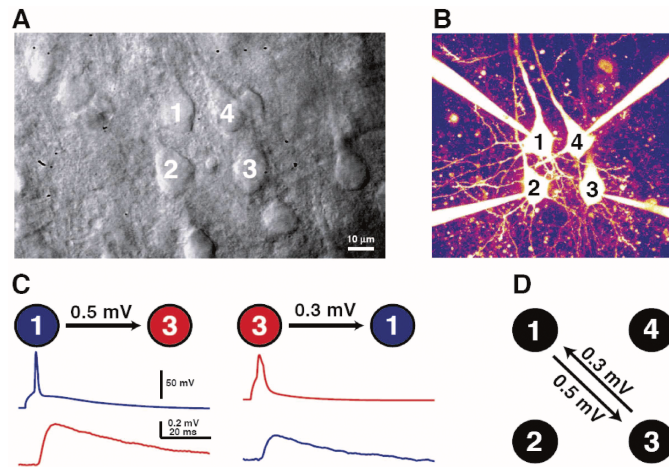


Figure 1: Song et al. use quadruple whole-cell recordings, observing simultaneously the membrane potential of four neurons. **A)** Contrast image showing four thick-tufted L5 neurons **B)** Fluorescent image of the same cells after patching on **C)** Evoking an action potential in the presynaptic neuron causes characteristic membrane potential change in the postsynaptic neuron **D)** Inferring synaptic connectivity from the EPSP waveform observed in C). Image from [Song et al. 2005](#).

While techniques for paired intracellular recordings are rapidly developing, their ability to capture connectivity patterns of large networks is yet very limited. To this date, the connectome of *C. Elegans* remains the outstanding exception of a connectivity configuration that has been fully mapped [Source]. Even in the state-of-the-art experiment conducted by Perin et al., using a setup capable of recording up to twelve neurons simultaneously, the authors note that an investigation of degree distribution was not carried out, due to lack of sufficient data [Perin, Berger, and Markram 2011](#).

Exploiting the benefits of a geometrical model

Working with a geometrical network model and its computational implementation, such restrictions disappear; the full information about the network, in form of its connectivity matrix, is given at point in time and can be easily queried for. Experiments that may take days to perform *in vivo*, can be completed in a matter of seconds *in silico*. As such, geometrical models lend themselves to extensive examination of their structural aspects.

In trying to exploit these advantages, two approaches present themselves. One may construct a network model that extrapolates the known biological configuration; a full structural examination of these networks could possibly expose relevant patterns not yet observed. For this approach a sophisticated understanding of the biological configuration is critical. Neuron morphology, however, is difficult to describe and extract.

*Extrapolation vs.
reduction*

For this analysis we suggest a reductionist approach. Having motivated an abstract model reflecting a cortical network's directional heterogeneity, we distinguish emerging patterns of connectivity, specific to directionally heterogeneous networks, from results, that only indirectly stem from the network's anisotropy, in the hopes to be able to characterize the significance of directional heterogeneity in structural connectivity of cortical circuits.

Structural aspects of the heterogeneous model

In this chapter we subject the directionally heterogeneous network model introduced in ?? to a critical analysis of its structural aspects. General network topology, as well as specific modes and patterns of connectivity, are to be identified and laid out for comparison with findings in biological neural networks.

In an effort to map out structural features that can be directly associated with the network's directional heterogeneity, it is crucial to differentiate such findings from results that are only indirectly caused by the network's anisotropy. To this end, already in ?? we developed a measure to quantify the degree of anisotropy prevalent in a given

*employing
anisotropy
measure*

network; throughout this chapter we will now frequently employ this measure to determine which structural aspects are originating from the network's heterogeneity, and which aspects are to be attributed solely to the network's distance dependency.

Accordingly, results from this investigation are categorized in two sections: The first section, 'Section 2' , describes structural aspects that can not be directly attributed to the model's anisotropy. The second section, 'Section 3' , then presents results that are truly features of network's directional heterogeneity.

BIBLIOGRAPHY

- Brette, Romain and Alain Destexhe (2012). *Handbook of neural activity measurement*. English. Cambridge: Cambridge University Press.
- Perin, Rodrigo, Thomas K. Berger, and Henry Markram (2011). A synaptic organizing principle for cortical neuronal groups. en. *Proceedings of the National Academy of Sciences*. PMID: 21383177.
- Roxin, Alex (2011). The Role of Degree Distribution in Shaping the Dynamics in Networks of Sparsely Connected Spiking Neurons. *Frontiers in Computational Neuroscience*. PMID: 21556129 PMCID: PMC3058136.
- Song, Sen, Per Jesper Sjöström, Markus Reigl, Sacha Nelson, and Dmitri B Chklovskii (2005). Highly Nonrandom Features of Synaptic Connectivity in Local Cortical Circuits. *PLoS Biol.*
- Sporns, Olaf (2007). Brain connectivity. *Scholarpedia*.
- Sporns, Olaf and Rolf Kötter (2004). Motifs in Brain Networks. *PLoS Biol.*
- Weckstrom, Matti (2010). Intracellular recording. *Scholarpedia*.
- Zhao, Liqiong, Bryce Beverlin, Theoden Netoff, and Duane Q. Nykamp (2011). Synchronization from Second Order Network Connectivity Statistics. *Frontiers in Computational Neuroscience*. PMID: 21779239 PMCID: PMC3134837.