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Microcircuits – Their structure, dynamics and role for brain function

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Microcircuits have been characterised as functional modules that act as elementary processing units bridging single cells and systems levels (Grillner & Graybiel, 2006). The brain, from the neocortex to the spinal cord, consists of various microcircuits, each serving specific functions. Examples of such functional modules include cortical columns of the sensory cortices, glomeruli in the olfactory systems, networks for the storage and recall of memories in the hippocampus and the prefrontal cortex, and neuronal circuits generating different aspects of motor behaviour. Understanding how neurons in microcircuits interact is one of the most fundamental questions in the neurosciences today. The goal of the current special issue is to provide a snapshot and a résumé of the current state-of-the-art of ongoing experimental and computational research on design principles and computational functions of various cortical microcircuits.

Tiesinga and Buia start this special issue by introducing a computational model based on the biased competition framework in order to explore the relation between V1 and V4 receptive field properties in spatial attention tasks. A number of simulations is performed that cast light on the circuits underlying stimulus selection and suppression. Results are consistent with general ideas behind biased competition, but the present work nicely demonstrates response properties for various stimulus conditions in a single network. The network also displayed a transition from more global alpha oscillations without stimuli to more localized beta/gamma range oscillations in the presence of stimuli.

Schrader, Gewaltig, Koerner and Koerner present a hierarchical spiking neuron model of the ventral pathway for pattern recognition. They propose that a first wave of spikes after stimulus presentation causes a (small) number of candidate representations to be formed quickly in the top-level of the hierarchy which become confined in a subsequent recurrent phase of processing that makes use of feedback for the disambiguation at different levels.

Binzegger, Douglas and Martin study the influence of neuroanatomical connectivity on information processing in a canonical cortical microcircuit of cat primary visual cortex. The laminar connectivity matrix indicate that the cortical circuit is dominated

by strong recurrent connections within superficial layers in contrast to deep layer structures where cells are connected more to neurons in other layers. A simple artificial linear-threshold neuron model is used to simulate and study the stability of the circuit dynamics. The simulations indicate that the recurrent connections in layer 2/3 dominate the circuit dynamics and move them close to the unstable regime. Stability is achieved by strong inhibition, which controls and reduces the dominance of excitatory feedback. In this simplified framework, the topology of the circuit is reconfigured dynamically by modifying the average inhibition threshold of the neurons. As the circuit becomes more active, the average inhibition becomes stronger and prunes the weak connections. This shifts the network from a more random topology to a more clustered small-world-like configuration.

Symes and Wennekers investigate the interdependence of local and long range connections in layer 2/3 in primary visual cortex. Their population mean field model demonstrates that the precise spatiotemporal spread of activity seen in the cortical slice results from long-range connections that target specific orientation domains while distinct regions of suppressed activity are shown to arise from local isotropic axonal projections. Distal excitatory activity resulting from long range axons is shaped by local interneurons similarly targeted by such connections. It is shown that response latencies of distal excitation are strongly influenced by frequency dependent facilitation and low threshold inhibition.

Friston and Kiebel present a theoretical paper aiming at modelling perception in cortical circuits from a general point of view of Bayesian modelling and the free-energy principle. An application of their approach to song generation and recognition in song-birds is also presented.

Maex and Steuber provide a very nice review of neural mechanisms underpinning retention of memory traces for periods of time from milliseconds to tens of seconds. The review is wide-ranging, providing snapshots of diverse mechanisms in different brain areas.

Hajos and Paulsen offer an excellent overview of microcircuit mechanisms of cortical gamma-frequency oscillations. Focusing on experimental data obtained in an *in vitro* model, the authors review discharge pattern and synaptic interactions of various neuron types of the hippocampal CA3 area during gamma activity. The authors conclude that reciprocal interaction between excitatory

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principal cells and inhibitory interneurons, in particular fast-spiking basket cells are of crucial importance for the synchronisation of the neurons and the emergence of the oscillatory population pattern.

Cutsuridis and Wennekers provide an overview of hippocampal network models in the context of learning and memory. Starting with classic conceptual models their review rapidly moves to biophysically motivated models implementing increasing detail of the anatomical structure and physiological properties with a focus on the role of microcircuit interactions in the induction of synaptic plasticity, encoding and subsequent recall of information.

Hasselmo and colleagues provide a thought-provoking exposition of the possibilities for coding and memory via phase relationships of oscillations. Specific application is given for the entorhinal cortex and hippocampus. Here it is known that firing phase, relative to the underlying theta rhythm is a better indication of location than place cell firing rate.

Zeldenrust and Wadmann provide a detailed analysis of the effects of fast and slow inhibitory loops on the firing characteristics of a pyramidal cell. In particular, they examine the prevalence of spiking and bursting and show that inhibition can act to 'speed up' the firing of the PC by switching it from bursting to single spiking mode.

Baker, Schubert, Levels, Bezgin, Bojak and Kötter investigate structure and dynamics of the rodent barrel cortex by using simultaneous multi-site extracellular recordings and focal stimulation in combination with multivariate data analysis. The authors show that stimulus-induced responses are highly reproducible and have characteristic spatiotemporal distribution of field potentials depending on the location of the stimulus. The authors propose that this method, especially when combined with pharmacological manipulation or performed in genetically modified organisms, is ideally suited for mapping synaptic mechanisms underlying field potentials and population activity in cortical microcircuits.

Linster and Cleland provide a concise and insightful review of olfactory bulb microcircuits. The review focuses on two important computational functions: decorrelation and normalization of odour perception. The authors conclude that multiple feedforward and feedback inhibitory circuits underlie these functions. While decorrelation is dependent on the local inhibitory mechanisms in columns exhibiting similar olfactory receptive fields, normalization requires distributed inhibitory control proportional to the global excitation level. The authors propose that these mechanisms reflect specialised computational functions essential for the non-topographical processing of sensory information.

Humphries, Wood and Gurney describes a large-scale model of striatum aiming to understand the basic computational function performed by these circuits in motor control. The focus of the study is on how fast-spiking GABAergic interneurons, interconnected by both mutual inhibitory synapses and gap junctions, control the short-term dynamics of medium spiny neurons (MSNs) in response to cortical input. Unexpectedly, the authors find that feed-forward inhibition mediated by the interneuron network can increase the firing rate of MSNs. They further find that in the absence of dopaminergic input, synchronised clusters of MSNs develop, an observation which is likely to have relevance for pathological states such as Parkinson's disease.

Durstewitz raises a provocative call to look at the detailed biophysics when developing models of brain networks. He focuses on the influence of NMDA receptors on network firing properties, showing how the highly non-linear response of these receptors can strongly influence the firing states of a neuron. How this might fit within the context of working memory is discussed.

References

- Grillner, S., & Graybiel, A. M. (2006). *Microcircuits: The interface between neurons and the global brain function*. MIT Press.