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Barrel cortex function

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ABSTRACT

Neocortex, the neuronal structure at the base of the remarkable cognitive skills of mammals, is a layered sheet of neuronal tissue composed of juxtaposed and interconnected columns. A cortical column is considered the basic module of cortical processing present in all cortical areas. It is believed to contain a characteristic microcircuit composed of a few thousands of neurons. The high degree of cortical segmentation into vertical columns and horizontal layers is a boon for scientific investigation because it eases the systematic dissection and functional analysis of intrinsic as well as extrinsic connections of the column. In this review we will argue that in order to understand neocortical function one needs to combine a *microscopic* view, elucidating the workings of the local columnar microcircuits, with a *macroscopic* view, which keeps track of the linkage of distant cortical modules in different behavioral contexts.

We will exemplify this strategy using the model system of vibrissal touch in mice and rats. On the macroscopic level vibrissal touch is an important sense for the subterranean rodents and has been honed by evolution to serve an array of distinct behaviors. Importantly, the vibrissae are moved actively to touch – requiring intricate sensorimotor interactions. Vibrissal touch, therefore, offers ample opportunities to relate different behavioral contexts to specific interactions of distant columns. On the microscopic level, the cortical modules in primary somatosensory cortex process touch inputs at highest magnification and discreteness – each whisker is represented by its own so-called barrel column. The cellular composition, intrinsic connectivity and functional aspects of the barrel column have been studied in great detail.

Building on the versatility of genetic tools available in rodents, new, highly selective and flexible cellular and molecular tools to monitor and manipulate neuronal activity have been devised. Researchers have started to combine these with advanced and highly precise behavioral methods, on par with the precision known from monkey preparations. Therefore, the vibrissal touch model system is exquisitely positioned to combine the microscopic with the macroscopic view and promises to be instrumental in our understanding of neocortical function.

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Contents

1. Introduction

Elucidating the function of cortical networks requires an interplay between anatomical and physiological analyses, as has been emphasized repeatedly by earlier reviews of cortical function (e.g. Douglas and Martin, 2007; O'Connor et al., 2009). Such an interactive approach will provide mechanistic ideas 'how' the cortical machinery might work. However, in order to decide between different mechanistic hypotheses of cortical function the question of 'what' is achieved by cortical processing will become increasingly important. For sensory systems this question is asked by studies on the physiology of perception (Parker and Newsome, 1998), involving simultaneous measurement of neuronal activity and the subject's behavior and percept.

So, what is the genuine function of the cerebral cortex? A traditional way to approach this question is to measure how neocortical circuits are involved in signal processing. The best way to do that is to investigate sensory systems, because the physical stimulus leading to activation of the cerebral cortex can be brought under tight experimental control. Measurement of neocortical information about a stimulus that we control precisely, may tell us something about the capability of the neocortex to process and to respond to this specific sensory input. The problem with this approach is that sub-cortical structures typically contain much more quantifiable stimulus information than the cerebral cortex. The conclusion from this has been that neocortical circuits either lose information, or at least represent it using highly intricate (e.g. nonlinear) ways (Wu et al., 2006). An alternative idea, however, is that sensory cortex is not mainly processing details of its inputs via ascending sensory pathways, but represents information about what else is going on in the brain. This tendency increases when going from sensory to associative cortical areas. Maybe the genuine cortical function has less to do with signal processing itself (in the narrow sense of the word; like the process needed to extract relevant sensory information from the output of sensory receptors), but rather with the proper organization and use of information in view of the demands and constraints of the specific situation the subject is in. This notion entails that it is the main function of neocortical processes to put externally and internally generated signals in context to allow for flexible goal-oriented behavior. In a second step, repeated processing within the same context leads to the learning of the respective behavior – possibly laid down as memory traces in cortical circuits (Fuster, 2009).

The view that associative and mnemonic aspects are at the core of neocortical function may solve the puzzle why cortical microcircuitry is similar across areas and species although so many different kinds of signals are dealt with (reaching from sensation via cognitive processing to motor functions). It is intuitive to assume that signal processing (again in the narrow sense of the word) is not done by the generalist neocortical neuronal architecture, but is often relayed to dedicated sub-cortical neuronal structures – an idea that is supported by the fact that every neocortical area is connected to many of them – often in a reciprocal manner (Felleman and van Essen, 1991; Diamond et al., 2008). In this framework, investigating neocortical function would not make much sense if the cerebral cortex is isolated physically, anesthetized or investigated in a highly rarefied experimental situation (e.g. probing it with point like stimuli). Rather, for a genuine understanding of neocortical function, its activity has to be probed in a behaving subject solving a task in an environment that offers a minimum of (experimentally controlled) contextual dependencies. Employing complex stimuli that show temporal and/or spatial contingencies that require contextual processing is a good start. Even better is to probe neocortical activity in different, meticulously controlled sensorimotor or cognitive situations.

All this would be well and good – were the neocortical structure and circuits not so complex. One column spanning a surface area of approximately 300 μm $\times$ 300 μm consists of some 10,000 neurons, composed of excitatory and inhibitory neurons, organized in different layers and with characteristic input and output connections (Lübke and Feldmeyer, 2007; Schubert et al., 2007; Lefort et al., 2009; Oberlaender et al., 2011b). An understanding of this complexity calls for very different types of experiments than the ones depicted in the last paragraph, namely highly precise analysis of neuronal morphology, connectivity and synaptic function – best performed in isolated preparations like neocortical slices or anesthetized in vivo preparations.

The conceptual and technical challenge to understand the function of the neocortex thus involves on one side a 'macroscopic' view of context dependencies and on the other a 'microscopic' view on the mechanisms of population, cellular, sub-cellular and

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