SUMMARY OF
Modeling cortical maps with *Topographica*

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Abstract

The biological function of cortical neurons can often be understood only in the context of large, highly interconnected networks. These networks typically form two-dimensional topographic maps, such as the retinotopic maps in the visual system. Computational simulations of these areas have led to valuable insights about how cortical topography develops and functions, but further progress is hindered by the lack of appropriate simulation tools. This paper introduces the *Topographica* map-level simulator, currently under development at the University of Texas at Austin. *Topographica* is designed to make large-scale, detailed models practical. The goal is to allow neuroscientists and computational scientists to understand how topographic maps and their connections organize and operate. This understanding will be crucial for integrating experimental observations into a comprehensive theory of cortical function.

Key words: simulation tools, cortical modeling, topographic maps, self-organization, development

1 Introduction

Much of the cortex of mammals can be partitioned into topographic maps [6]. These maps contain systematic two-dimensional representations of features relevant to sensory and motor processing, such as retinal position, sound frequency, line orientation, and motion direction [3, 7, 10]. Understanding the development and function of topographic maps is crucial for understanding brain function, and will require integrating large-scale experimental imaging results with single-unit studies of individual neurons and their connections.

Computational simulations have proven to be a powerful tool in this endeavor. In a simulation, it is possible to explore how topographic maps can emerge from the behavior of single neurons, both during development and during perceptual and motor processing in the adult. (For a review of this class of models, see [9].) However, the simulation tools currently available do not support simulations of topographic maps of highly interconnected units. Existing biologically oriented neural simulators, such as NEURON [5] and GENESIS [4], primarily focus on detailed studies of individual neurons or very small networks of them. Tools for simulating large populations of abstract units, such as PDP++ [8] and Matlab (www.mathworks.com), do not support efficient simulation of specific intracortical connections. Existing simulators also lack specific support

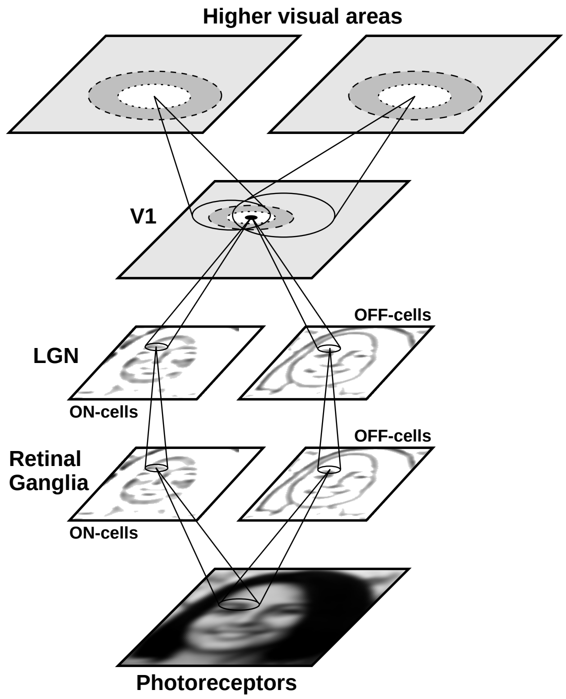

Fig. 1. **Topographica models.** This figure shows a sample *Topographica* model of the early visual system [1, 2]. In *Topographica*, models are composed of interconnected maps. Each visual area in this model is represented by one or more maps. For instance, the eye is represented by three maps: a map representing an array of photoreceptors, plus two maps representing retinal ganglion cells. Each of the maps can be coarse or detailed, plastic or fixed, as needed for a particular study. Maps are connected to other maps, and units within each map can be connected using lateral connections. For one cell in each map in the figure, sample connections are shown, including lateral connections in V1 and higher areas. Similar models can be used for topographic maps in somatosensory, auditory, and motor cortex.

for measuring topographic map structure or generating input patterns at the topographic map level.

This paper introduces the *Topographica* map-level simulator, which is designed to make it practical to simulate large-scale, detailed models of topographic maps. *Topographica* is being developed at the University of Texas at Austin as part of the Human Brain Project of the National Institutes of Mental Health. It is designed to complement the existing low-level and abstract simulators, focusing on biologically realistic networks of tens of thousands of neurons, forming topographic maps containing millions of connections.

To make such models practical, in *Topographica* the fundamental unit is a map rather than a neuron or a part of a neuron. Figure 1 illustrates the types of models supported by *Topographica*. For most simulations, the maps can be implemented at a high level, consisting of abstract firing-rate or integrate-and-fire neurons. When required for validation or for specific phenomena, *Topographica* will also support interfaces to maps developed using more detailed neuron models. Less-detailed maps can also be used temporarily, e.g. when interacting with the model in real time. Throughout, *Topographica* makes it simple to use an appropriate level of detail and complexity, as determined by the available computing power, phenomena of interest, and amount of biological data available for validation.

The fundamental goals of *Topographica* are to ensure that:

- Large map models execute quickly
- Visual, auditory, somatosensory, proprioceptive, and motor maps are supported
- Prototyping is fast and flexible
- New architectures and other extensions are easy to explore
- Maps can be analyzed easily using statistical tools

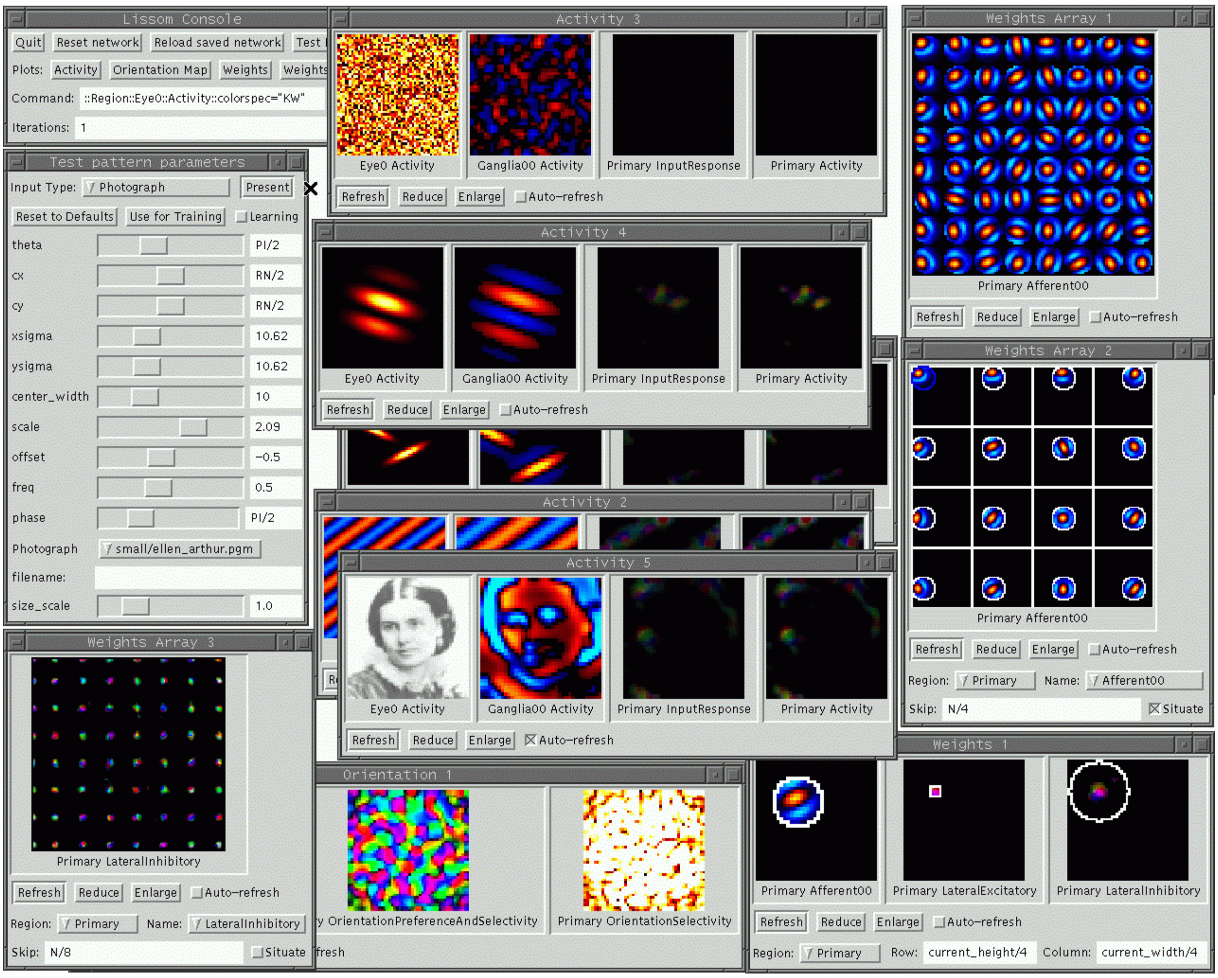

Fig. 2. **Software screenshot.** This image shows a sample session with LISSOM 4.0, a prototype version of *Topographica* that is available freely at `topographica.org`. Here the user is studying the behavior of an orientation map in the primary visual cortex (V1), using a model similar to the one depicted in figure 1. The window at the bottom labeled "Orientation" shows the self-organized orientation map and the orientation selectivity in V1. The windows labeled "Activity" show a sample visual image on the left, along with the responses of the retinal ganglia and V1 (labeled "Primary"). The input patterns were generated using the "Test Pattern" dialog at the left. The window labeled "Weights" shows the strengths of the connections to one neuron in V1. This neuron has afferent receptive fields in the ganglia and lateral receptive fields within V1. The afferent weights for an 8×8 and 4×4 sampling of the V1 neurons are shown in the "Weights Array" windows on the right; most neurons are selective for Gabor-like patches of oriented lines. The lateral connections for an 8×8 sampling of neurons are shown in the "Weights Array" window at the lower left; neurons tend to connect to their immediate neighbors and to distant neurons of the same orientation. This type of large-scale analysis is difficult with existing simulators, but *Topographica* is well suited for it.

- Model results can be validated against experimental data and
- The context of each model can be simulated easily, by including inputs and feedback from the environment and other parts of the nervous system

Figure 2 shows a screenshot from the current prototype of the software, available for free download at `topographica.org`. The first full release is scheduled for winter 2003-2004, and will include:

- Support for Windows, Mac, Linux, and UNIX platforms
- Parallel supercomputer support
- Cross-platform graphical user interface (GUI)
- User-extensible scripting interface
- Flexible rendering of artificial input patterns
- Photographic image and video input
- Libraries of map types, neuron models, connection types, learning rules
- Interfaces to NEURON, Matlab, and plotting and analysis libraries

Using these tools, we expect that neuroscientists and computational researchers will be able to answer many of the outstanding research questions about topographic maps, including what roles environmental and intrinsic cues play in map development, and what computations they perform in the adult. Other current research topics include understanding how object segmentation, grouping, and recognition are implemented in maps, and how feedback from higher areas and visual attention affect lower level responses. The simulator is designed throughout to be general and extensible, and so it will also be able to address new research questions that arise from future experimental work.

We plan to make several subsequent releases over the next few years, including user-contributed extensions and models. We will also set up an online repository for user contributions, so that researchers can share code and models. We believe this shared, extensible tool will be highly useful for the community of researchers working to understand the large-scale structure and function of the cortex.

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