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The use and abuse of large-scale brain models

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We provide an overview and comparison of several recent large-scale brain models. In addition to discussing challenges involved with building large neural models, we identify several expected benefits of pursuing such a research program. We argue that these benefits are only likely to be realized if two basic guidelines are made central to the pursuit. The first is that such models need to be intimately tied to behavior. The second is that models, and more importantly their underlying methods, should provide mechanisms for varying the level of simulated detail. Consequently, we express concerns with models that insist on a 'correct' amount of detail while expecting interesting behavior to simply *emerge*.

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Introduction

One central goal of neuroscience is to understand how complex processes in the brain give rise to complex behavior. Only recently has our understanding of the processes at work in the brain, and our ability to simulate complex processes in general, progressed to the point that this goal seems realistic. Advances in hardware have made the simulation of millions or even billions of neurons possible. Resources aimed at whole brain data collection have provided unprecedented views of brain anatomy and function that can help us to construct and verify large-scale models [1–3]. The quality of such data sets is only likely to improve with the progress of billion dollar projects such as the recently announced Brain Activity Map project (aka the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) initiative) [4], which intends to develop experimental methods for recording unprecedented numbers of neurons in an active neural circuit.

As such resources become available, it is critical to ask: How can we best make use of these resources to succinctly quantify our understanding of brain function? We believe that, given the analytic intractability of a system as complex and nonlinear as the brain, large-scale modeling will play a crucial role. That is, we must build a brain to know one. As Richard Feynman famously noted: "That which I cannot create, I do not understand" [5].

However, there are a wide variety of ways we might proceed in creating a simulated brain. Consequently, we review several past large-scale models to characterize different approaches (see also [6,7] for reviews), describe the benefits we might expect of such models, and ultimately discuss what lessons can be drawn regarding the continued development of ever larger and more sophisticated brain models. To be specific, we are focussing on large-scale brain models that span multiple brain areas and whose output is the product of large numbers of simulated neurons (e.g. over a million). These large-scale brain models are a subclass of large-scale neural simulations.

Notable large-scale brain models

Izhikevich and Edelman

One of the first brain-scale models ever developed was the 100 million neuron thalamocortical model developed by Izhikevich and Edelman [8]. It included 22 different types of multi-compartmental neurons in cortex and thalamus, wired together by about 500 million synapses, which captured synaptic dynamics including short-term plasticity and STDP. The model exhibited phenomena that are known to exist in the human brain, such as spontaneous activity and rhythms of spiking activity.

The Human Brain Project

One of the most highly publicized large-scale brain models is the Blue Brain Project, started in 2005 [9]. The Human Brain Project (HBP) [10••], which was recently approved for one billion euros of funding from the European Union, has the Blue Brain model as its centerpiece. The stated goal of the HBP is to build a working simulation of the entire human brain. The model is focused on simulating cortical columns, hypothesized cylindrical groups of approximately 100,000 neurons that make up the cerebral cortex of mammals [11,12], but see also [13]. The largest simulations of this model to date have included about a million neurons. Each neuron and synapse is simulated in a great deal of detail, taking into account ion channel composition, spatial morphology and detailed physiological data [14]. The majority of data used in the model is gathered from rodent slice experiments and connectivity is determined by the statistical properties of observed connectivity across slices [15]. The project is expected to allow "tracking the emergence of intelligence" [9].

The DARPA Synapse Project

Another large-scale model currently under development is part of the DARPA Synapse project [16]. This project was started in 2008, and the cortical model included in this project is based upon previous work simulating hundreds of millions of cortical neurons [17]. In contrast to the HBP, the Synapse project uses a simpler neuron model that includes neural spikes and spike-time-dependent plasticity (STDP), but little in the way of spatial morphology or ionic dynamics. As a result, many more individual neurons can be simulated simultaneously. They have recently reported a model with 500 billion neurons (5 times more than are in the human brain) [18••].

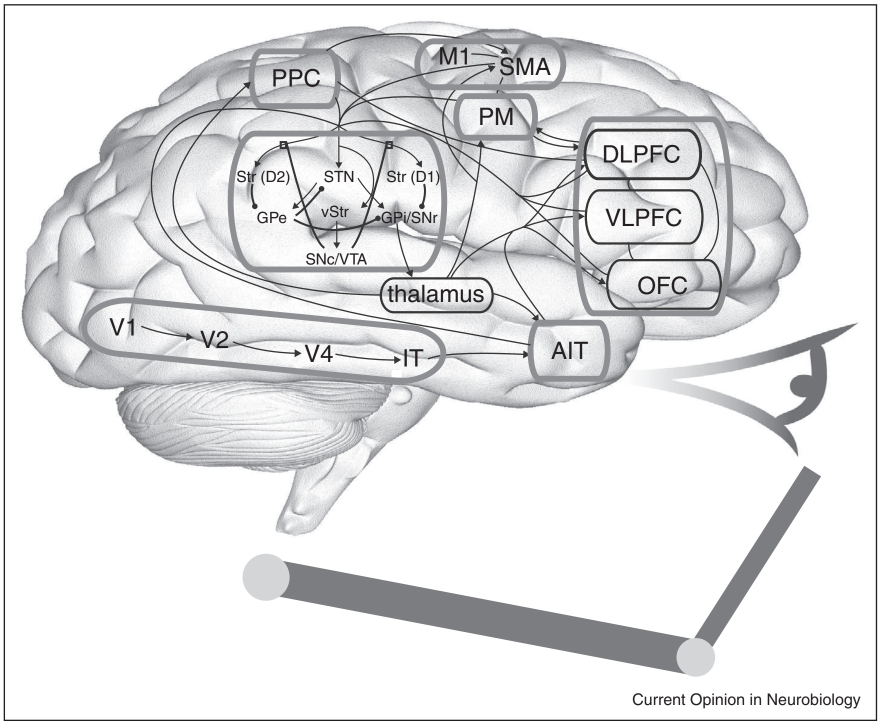
Spaun

Spaun [19••] is a large-scale brain model developed in our lab in 2012. In terms of the single neuron model employed, Spaun is similar to Synapse; it uses a simplified spiking model. In terms of number of cells, it is similar in scale to the HBP, as it uses 2.5 million neurons. The method used to design and construct the model combines the Neural Engineering Framework [20, NEF] and the Semantic Pointer Architecture [21•, SPA]. The NEF provides a quantitative, general approach for implementing high-dimensional nonlinear dynamical systems in networks of spiking neurons. It acts as a 'neural compiler' allowing high-level functional specifications to be mapped to connection weights in low-level spiking neural networks. The SPA provides a particular functional specification that captures central aspects of cortical and subcortical organization and behavior. The SPA defines a neurally plausible representational format (i.e. semantic pointers) that captures perceptual, motor, and cognitive representations. Spaun itself is a specific model that adheres to the SPA and was generated using the NEF. The model includes several cortical and subcortical structures, receiving input in the form of images through a single eye, and generating output by moving its single, physically modeled, arm (see Figure 1). Spaun is able to perform eight different perceptual, motor, and cognitive tasks in any order, without any changes to the model between tasks.

A comparison

The different choices regarding how to construct a large-scale model reflected in these examples has resulted in some friction. Henry Markram has criticized Modha's cat-scale neural model, calling it "trivial" and stating: "It is

Figure 1



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A high-level overview of the parts of the brain included in the Spaun model. Each brain area helps extend the functionality of Spaun, though none is specific to a single task. The implementation of a particular function by each area is well-supported by a variety of functional imaging and/or cellular data (see [19••]). The many subsystems are coordinated by a combination of their default connectivity and the flexible effective connectivity controlled by the basal ganglia (figure adapted from [19••] with permission).