Neural Networks 33 (2012) 275–290

Contents lists available at SciVerse ScienceDirect

Neural Networks

journal homepage: www.elsevier.com/locate/neunet

Complexity in a brain-inspired agent-based model

Karen E. Joyce [a,*], Paul J. Laurienti [b], Satoru Hayasaka [b,c]

[a] School of Biomedical Engineering and Sciences, Wake Forest University School of Medicine, Winston-Salem, NC 27157, USA
[b] Department of Radiology, Wake Forest University School of Medicine, Winston-Salem, NC 27157, USA
[c] Department of Biostatistical Sciences, Wake Forest University School of Medicine, Winston-Salem, NC 27157, USA

ARTICLE INFO

Article history:
Received 26 September 2011
Received in revised form 24 May 2012
Accepted 25 May 2012

Keywords:
Agent-based models
Human brain networks
Genetic algorithms
Cellular automata
Complexity
Artificial intelligence

ABSTRACT

An agent-based model consists of a set of agents representing the components of a system. These agents interact with each other according to rules designed with knowledge of the system in mind. Although rules control the low-level interactions of agents, these models often exhibit emergent behavior at the system level. We apply the agent-based modeling framework to functional brain imaging data. In this model, agents are defined by network nodes and represent brain regions, and links representing functional connectivity between nodes dictate which agents interact. A link between two regions may be positive or negative, depending on the correlation in functional activity between the two regions. Agents are either active or inactive, and systematically update based on the activity of their immediate neighbors. Their dynamics are observed over a certain time period starting from predetermined initial configurations. While the information received by each node is limited by the number of other nodes connected to it, we have shown that this model is capable of producing emergent behavior dependent on global information transfer. Specifically, the system is capable of solving well-described test problems, such as the density classification and synchronization problems. The model is capable of producing a wide range of behaviors varying greatly in complexity, including oscillations with cycles ranging from a few steps to hundreds, and non-repeating patterns over hundreds of thousands of time steps. We believe this wide dynamic range may impart the potential for this system to produce a myriad of brain-like functional states.

1. Introduction

A complex system is characterized by interconnected components which are typically quite simple, but when assembled as a whole exhibit emergent behavior that would not be predicted based on the behavior of each individual component alone (Mitchell, 2009). In other words, the emergent behavior of the system is not a simple sum of behaviors of all the constituent components. The brain is an excellent example of a complex system. A complete understanding of the biochemical processes that underlie the behavior of an individual neuron can never produce an explanation for processes such as decision making and emotion. In his paper entitled *More Is Different* (Anderson, 1972), Anderson makes the case that multiscale modeling approaches are necessary for modeling systems in the natural world. He advised against the reductionistic approach in which a system is condensed to its most basic constituent, studied *ad infinitum* at that level, and the resultant conclusions are applied to the system at the macroscopic level. It is becoming increasingly apparent that multiscale approaches will be necessary to understand many of the systems in our universe. In fact, in work by Gu, Weedbrook, Perales, and Nielsen (2009), an infinite square ising model was used as formal evidence of Anderson's assertion. In this work, the ising model was used to represent a cellular automaton (CA), a two-dimensional lattice of cells that communicate with adjacent neighbors. Inputs to the CA were encoded as the ground state of the ising block, and the model stepped through time according to an update function. Many macroscopic features of the system were shown to be undecidable based solely on the microscopic properties. They concluded that a reductionistic "theory of everything" is necessary, but is unlikely to be solely sufficient to describe a complex system with emergent behavior. Clearly such a theory of everything would be inapplicable in the brain. However, by modeling the way neurons interact with each other en masse, a bottom-up modeling approach may be able to reproduce some of the complex behaviors inherent to the brain. One such approach is agent-based modeling.

An agent-based model (ABM) consists of a set of individuals, or agents, representing the components of a system. Agents are allowed to interact with each other according to a rule, or a set of rules, designed with knowledge of the system in mind. Agent-based models are most valuable in systems that exhibit

* Correspondence to: School of Biomedical Engineering and Sciences, Wake Forest University School of Medicine, Medical Center Boulevard, Winston-Salem, NC 27157, USA. Tel.: +1 336 716 0473; fax: +1 336 716 0798.
E-mail address: kajoyce@wakehealth.edu (K.E. Joyce).

0893-6080/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.neunet.2012.05.012

complex emergent behavior. Although rules only control the low-level interactions of agents, these models often exhibit emergent behavior on the level of the system. For example, the Boids simulation (Reynolds, 1987) is one such ABM, where the agents in the simulation are birds, and the very simple rules they obey are cohesion (fly close to your neighbors), separation (not too close), and alignment (in the same direction). These simple rules will, over a few iterations, form a coordinated flock out of any random initial configuration of birds.

The brain exhibits hierarchy in both structural (Bullmore & Sporns, 2009; Hagmann et al., 2008) and functional (Bullmore & Sporns, 2009; Meunier, Achard, Morcom, & Bullmore, 2008; Meunier, Lambiotte, Fornito, Ershe, & Bullmore, 2009) organization. Due to this hierarchical organization, the brain can be modeled at various scales ranging from the microscale level of the individual neuron to the macroscale level of the complete brain (Hayasaka & Laurienti, 2010; Jirsa, Sporns, Breakspear, Deco, & Mcintosh, 2010). A microscale model of the brain including each of approximately 300 billion neurons would be difficult to implement and to interpret. Such a model would be just as complex as the brain, negating the advantage of producing a more simplified representation. On the other hand, a macroscale model at the whole-brain scale would include a top-down definition of the system. Every behavior of the system would necessarily be individually defined. Between these two extremes lies a mesoscale model, wherein the brain model is composed of interdependent regions performing mesoscale interactions resulting in macroscale behaviors.

We introduce a brain-inspired mesoscale agent-based model that we call the agent-based brain-inspired model (ABBM). The model is built upon a brain network measured using functional brain imaging data from humans. The ABBM uses rules that are based on the microscale level of the neuron and applies those rules at the mesoscale level of pools of neurons. These rules are used by each mesoscale brain region to process the information it receives and make a decision about whether to turn on or turn off. This decision-making process is analogous to a single neuron on the microscale integrating information received from neighboring neurons and firing if the excitation exceeds a minimum voltage. In this way, the ABBM uses principles from the microscale level and applies them to the mesoscale level.

Our proposed framework is a more generalized version of a neural network model, such as that described by Goltsev, Abreu, Dorogovtsev, and Mendes (2010). Their model utilized a set of excitatory and inhibitory neurons arranged as a network, and behaviors were driven by equations. The model exhibited oscillatory, chaotic, and critical behaviors. Other equation-based neural network models have demonstrated transitions from disordered chaos to global synchronization (Percha, Dzakpasu, & Zochowski, 2005). Contrary to equation-based modeling, our agent-based model utilizes interdependent agents driven by cellular automaton rules. Cellular automata have been studied thoroughly in resources such as (Bak, Chen, & Creutz, 1989; Braga, Cattaneo, Flocchini, & Vogliotti, 1995; Cook, 2004; Wolfram, 2002). It is typical that equation-based and agent-based models are capable of producing similar results, but agent-based models are often considered more intuitive as they produce results that are more easily interpreted (Parunak, Savit, & Riolo, 1998). Edward Fredkin has noted a distinct difference between cellular automata and equation-based models as noted by Wright (1988)—"You can predict a future state of a system susceptible to the analytic approach without figuring out what states it will occupy between now and then, but in the case of many cellular automata, you must go through all the intermediate states to find out what the end will be like: there is no way to know the future except to watch it unfold". Some cellular automata, including Conway's Game of Life, have been shown to be capable of universal computation (Bak et al., 1989; Cook, 2004), meaning that these systems are capable of computing any computable sequence and can replicate any computer program.

Some neural network models utilize network structure based on real world systems, such as those in Goltsev et al. (2010), Grinstein and Linsker (2004) and Percha et al. (2005). For example, Grinstein and Linsker (2004) investigated the importance of the underlying network structure in defining the system dynamics of neural networks. Their neural network utilized Hopfield-type dynamical rules and was engineered such that the degree distribution of the network reflected topology that commonly occurs in self-organized networks. This design enabled the neural network to produce synchronous behavior and oscillatory sequences of neural activity commonly seen in experimental data. Likewise, the agent-based brain-inspired model studied here is an extension of the functional brain networks that are currently used to study the functional interactions between brain regions. A functional brain network is a set of nodes and pathways between nodes representing the way in which regions of the brain communicate to perform a task. To clarify, these connections do not necessarily represent physical white matter tracts connecting neuronal cell bodies, but instead represent correlations in functional activity as measured through functional magnetic resonance imaging (fMRI). Functional brain networks are distinct from traditional fMRI data. Traditional fMRI data show which regions of the brain are active during a particular task. In contrast, functional brain networks consider all regions of the brain simultaneously by treating the brain as a network of interconnected and interdependent regions. The distinct advantage of a network-based approach of modeling the brain is that it does not focus on individual brain regions, but evaluates the interactions between all brain regions. This network-based approach has enabled us for the first time to model brain dynamics as described in this paper. In our model, agents are defined by functional network nodes representing brain regions, and functional links between nodes dictate which agents are allowed to interact. The utilization of functional brain networks derived from human data is a major strength of this approach.

While the information received by each node is limited by the number of other nodes connected to it, we show here that this model is capable of producing emergent behavior at the level of the system. We apply this system to well-described test problems and additionally demonstrate the ability of the model to produce a wide range of behaviors. A combination of true brain network structure and cellular automata rules results in model output with a wide dynamic range, and imparts the potential to produce a myriad of brain-like functional states.

2. Methods

2.1. Framework for an agent-based brain-inspired model

The agent-based brain-inspired model (ABBM) is an agent-based model with connectivity structure that is derived from brain network data. The underlying brain network dictates which brain nodes can interact with one another by explicitly specifying the existence of connections. The brain nodes can be selected to represent the brain network at different levels, from the level of neurons to anatomical parcellation of the cortex. In this work, each node represents a distinct brain anatomical area defined by the AAL (automated anatomical labeling) atlas (Tzourio-Mazoyer et al., 2002), and connections between the nodes were determined using fMRI time series data as is described, for example, in Bullmore and Sporns (2009). Although we used fMRI data to define connections, the framework may be applied to any functional or structural network derived from other imaging modalities or direct methods such as histology.