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A plausible method for assembling a neural circuit for decision-making

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ABSTRACT

Neuroscience seeks to understand how neural circuits lead to behavior. However, the gap between circuits and behavior is too wide. To explore how the microscopic neural activities leads to macroscopic behavioral control strategy, we considered the behaviors that humans and animals exhibit following some basic control rules, which can be described by simple logic language. The pulse mode of biological neurons is viewed as an expression of logical propositions, and a circuit constructed by biological neurons is seen as an equivalent achievement of logical operations (McCulloch & Pitts, 1943). And we know that any one complex logical operation can be equivalent to a logical expression that only contains three basic operations. We assume the logic-like operation as the one kind of "canonical computations" in the brain. This paper first designed the functional circuits to achieve the basic logic-like operations (And-like, Or-like, Negative-like) by spiking neuron model based on the known neurophysiological properties, and then, using the functional networks constructed a possible neural circuit for decision logic of animal's behavior. Finally, we simulated a decision-making process from both microcosmic neural activities and macro behavior. The contributions of this study is that we extend our understanding that treating the neurons, constituting neural circuits and its working principle from a logical perspective under the premise of strict compliance with the neural electrophysiological characteristics and anatomical facts. In addition, this study provides a general approach for constructing the neural circuits to implement the behavioral control logic. This study may be useful for us to understand how the microscopic activities of the nervous system lead to the macroscopic animal behavior.

Introduction

Wide gap existing between the circuit and behavior

In nature, both human and inferior insects can adapt to the environment and exhibit stable behavior. For example, insects can use the polarized light to navigate (Horváth & Varjú, 2013), and bees report the distance and azimuth with different dances so other bees can locate nectar or pollen based on dance information (Frisch, 1967). As long as these behaviors are not stochastic, we can assume that there must be specific neural functional circuits in biological nervous systems that lead to these behaviors. Stable behaviors are controlled by the specific neural circuits, and action potential (AP, Spike) firing within circuits as well as collaboration among neurons in the circuits generates basic animal behavior. *However, the inner neuromechanism about how neural activities can lead to a specific behavior is still unclear?*

For the brain as a complex system, three distinct levels should be understood, i.e., behavior level, algorithm level and implementational level, which is famously known as Marr's tri-level hypothesis (Marr, 1982). The benefit of this clear distinction is that researchers can focus on a certain level and do much research purposefully. As shown in Fig. 1, marr approach applied to computers and brains, as we know, all applications in the computer can be reduced to the most primitive operations (Logic instructions) of CPU, but we still unclear how the neural activities lead the behavior? The gap between neuron and behavior is still wide (Carandini, 2012). Without a clear link to behavior and computational mechanism, it's really hard to understand what is computed in these simulations, and "we are missing the fundamental purpose of neuroscience: to understand the relation between brains and behavior" (Eliasmith & Trujillo, 2014). Therefore, "We sorely need a foundational mechanistic, computational framework to understand how the elements of the brain work together to form functional units and ultimately generate the complex cognitive behaviors" (Brown, 2014). Much Research indicate that the nervous system can handle complex tasks by combining and repeating a core set of canonical neural computations, which is a mediate level between neurons' activity and behavior (Carandini & Heeger, 2012). Understanding these canonical computations in a nervous system helps us to reveal the computational mechanism from neurons to behavior.

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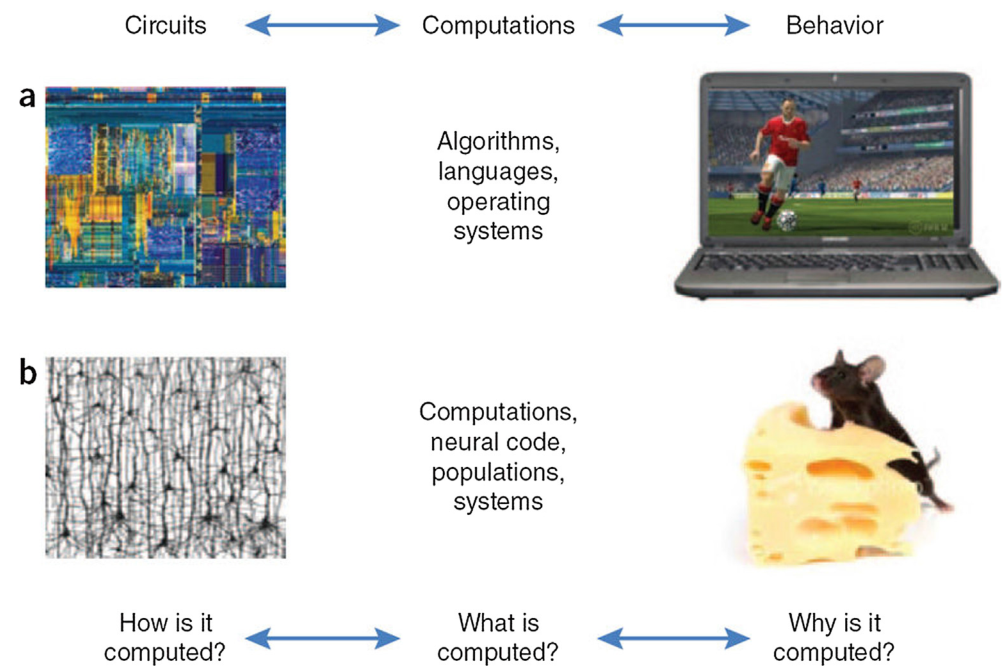

Fig. 1. Marr approach applied to computers and brains (from (Carandini, 2012)). (a). The wiring of a fraction of an CPU and a laptop playing a game; (b). Neurons in cortex and a mouse engaged in a behavior.

Why do we use logical rules to describe the behavior?

As we know, logic may be the most basic level and the simplest theory that can be restored under the framework of natural philosophy. Since, the logic reflects the most basic requirement that a behavior can successfully implement, and it is a necessary condition of any specific implementation required to perform these basic functions. We believe that the rules through which animals control their behavior can be described by logic language. In order for a biological nervous system to achieve a specific function or computation, its structure must be sufficiently complex to achieve the basic logic. Biological neural systems need to cope with a variety of tasks, and each task had its own internal control logic. Therefore, there may be many types of neural circuits to achieve various logical rules in the nervous system. From the perspective of logic, any type of behavioral logic can be formally described; the simplest form is propositional logical expression. With this reliable and complete formal language, we can accurately describe the basic logical rules with which behaviors comply. This set of logical rules has different implementations in different operating environments. For example, it is a strictly defined program in a computer-controlled automatic control system. How can a set of logical rules be achieved in an organism or, more precisely, in a biological nervous system? In other words, how do biological neurons and circuits composed of neurons perform these logical operations?

Furthermore, when we consider more anatomical and electrophysiological properties of biological neurons, can we find a more realistic way to achieve it? Since decision-making behavior in animals essentially implements a series of logical operations, how do biological neurons perform basic logical operations? We assume the basic logical operations as some neural computations in a nervous system. For example, how do neurons achieve the operations of propositional logic. Moreover, with different firing patterns of neurons and the synergistic connections between pyramidal neurons and intermediate neurons, can the nervous system assemble a circuit to achieve a set of specific logical rules?

We do not declare that the nervous system is the "two-valued logic". As we know, logic may be the most basic level and the simplest theory that can be restored under the framework of natural philosophy. We believe that the nervous system can perform the function of the "two-valued logic". All of those considerations are based on the signal processing mechanism of biological neurons. *The "two-valued logic" is the functional addressing for the neural circuits, but not to mean accurate logical computation. The name "Logic-like" was used to distinguish from the "Logic".* One consideration of the fault-tolerant designs is that a group of neurons instead of single neuron was used as basic unit, since biologic neurons working asynchronously and the fluctuation of firing rate. Our design is strictly consistent with neurobiological findings. On the contrary, the artificial neural networks commonly used in the field of machine learning and artificial intelligence is a purely engineering strategy, which is short of neurobiological basis in such as the neuron model, neuron type, layer number, feedback mechanism, learning mechanism, learning efficiency and so on (Nikolić, 2017). Therefore, our model is not based on the latest machine learning methods, but trying to refer to more neurobiological constraints to understand the changes of the internal circuitry when an animal carries a decision-making behavior.

Our approach

As we know, these logic gates can be implemented by non-biologically accurate artificial neurons very easily and compactly. However, the aim of our work is not to construct the neural network to achieve the logical operations. As shown in Fig. 2, we try to explore how the microscopic neural activities (as shown in Fig. 2(c)) can systematically explain the logical rationality of macroscopic behavior (as shown in Fig. 2(a): decision-making behavior), we proposed a general method that assembling the basic functional circuit to construct the neural circuit to achieve the control rules that decision-making behavior follows. We focus on a computational framework to extend our understanding how the elements of the brain work together to form functional units and ultimately generate the cognitive behaviors. Compared with simply collecting more experimental results and hoping these results will automatically reveal the complex mechanism of brain, "A 'top-down' approach, exploring plausible mechanisms in the context of