Available online at www.sciencedirect.com
ScienceDirect
BioSystems 90 (2007) 903–910
www.elsevier.com/locate/biosystems

A neural circuit model forming semantic network with exception using spike-timing-dependent plasticity of inhibitory synapses

Kazushi Murakoshi [a,b,*], Kyoji Suganuma [a]

[a] Department of Knowledge-Based Information Engineering, Toyohashi University of Technology, 1-1 Hibarigaoka, Tenpaku-cho, Toyohashi 441-8580, Japan
[b] Media Science Research Center, Toyohashi University of Technology, Japan

Received 22 March 2007; received in revised form 1 June 2007; accepted 4 June 2007

Abstract

We propose a neural circuit model forming a semantic network with exceptions using the spike-timing-dependent plasticity (STDP) of inhibitory synapses. To evaluate the proposed model, we conducted nine types of computer simulation by combining the three STDP rules for inhibitory synapses and the three spike pairing rules. The simulation results obtained with the STDP rule for inhibitory synapses by Haas et al. [Haas, J.S., Nowotny, T., Abarbanel, H.D.I., 2006, Spike-timing-dependent plasticity of inhibitory synapses in the entorhinal cortex. J. Neurophysiol. 96, 3305–3313] are successful, whereas, the other results are unsuccessful. The results and examinations suggested that the inhibitory connection from the concept linked with an exceptional feature to the general feature is necessary for forming a semantic network with an exception.

Keywords: Spike-timing-dependent plasticity; Inhibitory connection; Semantic network; Exception

1. Introduction

The role of memory is important for human high-order functions such as thought, motion, and recognition; high-order functions cannot be performed in the absence of memory. There are two major forms of memory, episodic memory and semantic memory, which are both declarative (Tulving, 1972; Squire, 1987). Episodic memory is supposed to deal with individual episodes definable with respect to time and place while semantic memory contains impersonal facts undefinable in terms of time and place. The semantic network model (Collins and Quillian, 1969; Collins and Loftus, 1975) is proposed as a structure model of semantic memory. A semantic network is an oriented diagram in which nodes represent actual objects and arcs represent semantic relationships between these objects. However, the semantic network model does not have a process for constructing a semantic network.

Kobayashi and Murakoshi (2007) have proposed a neural circuit model forming a semantic network in the neocortex from direct input and episodic memory in the hippocampus using spike-timing-dependent plasticity (STDP) (Froemke and Dan, 2002), based on the hippocampus neural circuit model forming episodic memory (Ito et al., 2003). STDP is a minute time resolution version of the well-known Hebb learning rule. In the model (Kobayashi and Murakoshi, 2007), for example, after inputs such as “a canary is a bird” and “a bird can fly” are memorized, the output words “canary”, “bird”,

* Corresponding author at: Department of Knowledge-Based Information Engineering, Toyohashi University of Technology, 1-1 Hibarigaoka, Tenpaku-cho, Toyohashi 441-8580, Japan.
Tel.: +81 532 44 6899; fax: +81 532 44 6873.
E-mail address: mura@tutkie.tut.ac.jp (K. Murakoshi).

0303-2647/$ – see front matter © 2007 Elsevier Ireland Ltd. All rights reserved.
doi:10.1016/j.biosystems.2007.06.001

and “can fly” are successively recalled by presenting the word “canary”. Such results show that the model is able to form a semantic network.

However, the semantic network formed by the model proposed by Kobayashi and Murakoshi (2007) cannot represent an exception. An example of an exception is described as follows. In the case that “a canary is a bird”, “a bird can fly”, “an ostrich is a bird”, and “an ostrich cannot fly” are presented, the exception is that “the ostrich is a bird *but* cannot fly” in contrast to the general fact that “birds can *generally* fly”. We examine whether the model (Kobayashi and Murakoshi, 2007) can learn the relations with an exception: “‘canary’ and ‘bird’ ”, “‘ostrich’ and ‘bird’ ”, “‘bird’ and ‘can fly’ ”, and “‘ostrich’ and ‘cannot fly’ ”. As a result, “can fly” is additionally recalled with “cannot fly” for the input “ostrich”, whereas, “can fly” is only recalled for the input “canary”. That is, the memory retrieval process of a semantic network with an exception is not perfectly accomplished using the model (Kobayashi and Murakoshi, 2007). For successful recall, any suppression of the output “can fly” for the input “ostrich” is necessary. In the model proposed by Kobayashi and Murakoshi (2007), only excitatory connections are used. Thus, we surmise that inhibitory connections are important for forming a semantic network with an exception in a neural circuit.

In this paper, we propose a neural circuit model forming a semantic network with exceptions using the spike-timing-dependent plasticity (STDP) of inhibitory synapses. To evaluate the proposed model, we conduct computer simulations. Because some types of STDP of inhibitory synapses are physiologically observed, we simulate each type of STDP. Additionally, since some rules for determining spike pairs are assumed, we examine each rule. It is expected that the results of computer simulations will clarify the role of inhibitory connections in memory with an exception.

The remainder of this paper is organized as follows: in Section 2, we introduce STDP and topics related to STDP. Section 3 proposes a neural circuit model forming a semantic network with an exception. Section 4 shows the results of our computer simulation, and discusses how to form a semantic network using the STDP of inhibitory synapses. Section 5 presents our conclusions.

2. Spike-timing-dependent plasticity

In this section, we introduce spike-timing-dependent plasticity (STDP), which is used in the proposed model shown in Section 3. STDP is a special Hebbian form of synaptic plasticity where the relative timing of pre- and postsynaptic spikes determines the change in synaptic weight. STDP is considered as a neural basis of memory storage. There are two types of STDP: STDPs of excitatory and inhibitory synapses. Since the profiles of these STDPs are derived from the repetitive applications of spike pairs, some rules for determining spike pairs must be assumed in two trains of numerous spikes.

In Section 2.1, we briefly introduce the STDP of excitatory synapses. Section 2.2 describes some types of STDP of inhibitory synapses. Section 3 explains some rules for determining spike pairs.

2.1. *STDP of excitatory synapse*

The relation of synaptic plasticity for excitatory synapses with the temporal difference between presynaptic and postsynaptic activations has been electrophysiologically observed (Markram et al., 1997; Bi and Poo, 1998; Froemke and Dan, 2002). From the relation, postsynaptic potentials arriving after presynaptic potentials induce long-term potentiation, and postsynaptic potentials arriving before presynaptic potentials induce long-term depression. Froemke and Dan (2002) have derived a numerical description of the increase and decrease rates of synaptic plasticity $F(\Delta t)$ [%] from electrophysiological data as follows:

$$F(\Delta t) = \begin{cases} 102 \exp\left(-\dfrac{|\Delta t|}{15.5}\right) & (\Delta t > 0) \\ -52 \exp\left(-\dfrac{|\Delta t|}{33.2}\right) & (\Delta t < 0) \end{cases} \tag{1}$$

Here, Δt (ms) is the temporal difference from a postsynaptic spike to a presynaptic spike.

2.2. *STDP of inhibitory synapse*

Some relations of synaptic plasticity for inhibitory synapses with temporal difference between presynaptic and postsynaptic activations have been electrophysiologically observed (Holmgren and Zilberter, 2001; Woodin et al., 2006; Haas et al., 2006). Since these observations are quite different, each profile of the STDP of inhibitory synapses is described as follows.

Holmgren and Zilberter (2001) have observed the changes in the efficacy of inhibitory postsynaptic potential depending on the temporal difference between pre- and postsynaptic potentials by experiments using cortical slices of rats. In their experiments, a conditioning train of 10 backpropagating dendritic action potentials (APs) was initiated by 5-ms current injections in the soma of a pyramidal neuron as a postsynaptic neuron at 50 Hz. In a presynaptic neuron, an AP was initi-