

A prefronto-parietal network model with feedforward and feedback connections

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Abstract

Computational study suggested that the prefrontal cortex (PFC) can perform fundamental operations of multiple target representations (Tanaka 2002). The cortical network of the PFC and the posterior parietal cortex (PPC) plays central roles in spatial working memory processing and attention. To investigate how the feedforward and feedback connections between the PFC and the PPC, as well as the intracortical circuits, contribute to such processes, this paper analyzes a network model of the prefrontal and posterior parietal cortices, proposed recently (Tanaka, submitted). The relevance of the layer-specific corticocortical connections to the neuronal activity of both areas is argued.

Keywords: Attention; Feedback; Feedforward; Posterior parietal cortex; Prefrontal cortex; Spatial working memory

Introduction

Dopamine D1 receptor activation exhibits "inverted-U shape" modulation of memory fields (Williams et al. 1995; Goldman-Rakic et al. 2000; Yamashita and Tanaka 2002). However, how slight deviation of the dopamine level in the normal range alters the prefrontal cortical (PFC) circuit dynamics is unknown. Recently, Tanaka (2002) addressed this issue via computer simulation of a model PFC circuit with dopamine effects. The results suggest the possibility that the PFC circuit can switch several different modes of cognitive operations of multi-target spatial working memory, such as replacement, addition, and rejection, by changing a few circuit parameters. Such operations may be performed in cooperation with several areas. The PFC and the posterior parietal cortex (PPC) are considered to play central roles in spatial working memory processing (Chafee et al. 1998; 2000). However, how these two areas contribute to the processing is unknown yet. Chafee et al. (1998, 2000) reported very similar neuronal activities of these areas of macaque monkeys during performing visuospatial working memory. They argued that the resemblance of the neuronal activities is compatible with the notion of concurrent processing in these areas. This does not, however, necessarily mean that these two areas contribute equally to visuospatial working memory processing. To delineate the signal flow inside the PFC-PPC network for visuospatial working memory processing, this article analyzes a global network model of the PFC and the PPC, which has been proposed recently (Tanaka, submitted).

Model

The cortical areas (PFC and PPC) are modeled by the networks connecting with each other. Both areas have three layers (superficial, intermediate, and deep) and contain pyramidal cells and interneurons. The PFC circuit model is based on the model developed by Tanaka (2001, 2002). The PPC has essentially the same architecture with the PFC, but has different layer specificity of the connections with the PFC. The layer specificity of the connections with the two areas obey the rule proposed by Barbas and Rempel-Clower (1997).

The model contains 2160 pyramidal cells and 720 interneurons (2880 in all). The neurons are described by a leaky integrate-and-fire neuron model (Tanaka 2001, 2002). The ion channels include: AMPA, NMDA, Nap, GABA_A, K(Ca), and leak.

Results

The PPC neurons in the intermediate layer exhibit transient response to the cue-related input. This activity is transmitted through the intracortical circuit to activate the PPC neurons in the superficial and deep layers. The activity in the superficial layer then transmitted to the PFC via the feedforward connections. The PFC neurons exhibit phasic (in the intermediate layer) or tonic activity (in the superficial and deep layers). Due to the strong recurrent excitation regulated by the local inhibition, the sustained activities of the PFC neurons have well-tuned directional selectivity. The activity profiles are well fitted by the gaussian function. The maximum firing rate of the delay-period activity is around 20-40 sp/s.

As the feedback connections become weaker, the PPC is off-lined from the PFC working memory system, in which the neurons fire tonically during the delay period. The PPC neurons exhibit only transient responses to the cue-related inputs. As long as the feedforward connections are strong enough, however, the cue information is transmitted to the PFC. That is, the loading of the working memory depends on the strength of the feedforward connections from the PPC to the PFC. Too strong connections, however, evoke background activity in the PFC neurons that is too noisy to form proper working memory.

Weak feedforward connections off-line the PFC from the afferent sensory inputs. In this mode, the PFC does not load newly coming inputs. Instead, this increases the robustness of the activity of the PFC neurons. The activity of the PFC neurons is readily reflects on the activity of the PPC neurons by using the intact feedback connections.

Once the two areas are connected reciprocally with regulated strengths, the neuronal activities of the two areas show resemblance. That is, the neurons in both areas behave concurrently to process the spatial working memory. The neurons in both areas (in the superficial and deep layers) exhibit similar sustained activities. The neurons in the intermediate layer of both areas show phasic activities. Although the activities are similar in both areas, the latency of the response to the cue-related input in the PPC precedes that in the PFC by about 50-100 ms.

Discussion

The layer specificity of the corticocortical connections in this model essentially obeys the rule proposed by Barbas and Rempel-Clower (1997). The concurrent mode of this model accounts for the similar activities of neurons of the PFC and the PPC reported by Chafee and Goldman-Rakic (1998; 2000). The simulation shows

the difference in the latencies of the responses to the cue-related input between the PFC and the PPC, as reported by Chafee and Goldman-Rakic (1998; 2000). This model reproduces this concurrent mode when the strengths of both feedforward and feedback connections are strong enough.

Arnsten and Goldman-Rakic argued that stress may take the PFC “off-line” to allow more habitual responses mediated by the posterior cortical and subcortical structures to regulate behavior (Arnsten 1998; Arnsten and Goldman-Rakic 1998). In this case, catecholamines, such as dopamine and norepinephrine may have powerful effects to switch the PFC on- or off-line (Arnsten 1998). Involvement of dopamine in cognitive operations has been suggested recently (Tanaka 2002). These issues are to be studied.