Simulation of resting-state neural activity in a loop circuit of the cerebral cortex, basal ganglia, cerebellum, and thalamus using NEST simulator

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Abstract—Motor and cognitive functions of the brain are realized by multiple types of neurons interacting within multiple loop circuits. In order to investigate the dynamic nature of the whole-brain network, we built and linked biologically-grounded models of the cerebral cortex, basal ganglia, cerebellum, and thalamus, as an extendable mammalian whole-brain. We fixed the connections based on experimental data and adjusted cellular parameters to replicate resting-state activities. Integrated simulations using a hybrid parallelization approach on the K-computer showed a good strong-scaling performance and clarified the issues in further scaling the model on Fugaku.

Keywords—**A whole-brain model, Large-scale simulation, Resting-state activity, NEST simulator, K-computer**

1 Introduction

The cerebral cortex (Ctx), basal ganglia (BG), cerebellum (CB), and thalamus (TH), which make up more than 90% of neurons in the mammalian brain, form a loop circuit (CBCT circuit; Fig. 1). The CBCT circuit is known to realize various types of information processing, such as motor control and decision making [1]. To elucidate the function of the CBCT circuit, it is crucial to understand how its components interact at the cellular level. Here we constructed a spiking network model of the CBCT circuit using NEST simulator [2] and performed large-scale simulations using K-computer [3] through collaborative work across multiple labs that are specialized in modeling different brain regions.

2 Method

2.1 CBCT model

The CBCT circuit is modeled as a layered sheet type of spiking neural network using the NEST simulator (Fig. 1 and 2). All neurons and synaptic connections are modeled using a leaky integrate-and-fire neuron model and conductance-based synapse model, respectively (Table 1). We fix the connections based on anatomical data and adjust Poisson noise or bias current to keep mean firing rates of neuron types to match those physiologically reported.

2.1.1 Individual regions in CBCT model

The model of Ctx consists of the primary motor cortex (M1) and the primary somatosensory cortex (S1). Connections of M1 and S1 are developed as in [4].

The model of BG is based on [5] and incorporates a realistic topological organization for its connections with Ctx and TH models. Connections are focused or diffused and incorporate AMPA and NMDA receptors for synapses from S1, M1 and TH. The BG, model reproduces resting state (Fig.3) and action selection.

The model of CB consists of two regions connected with S1 and M1. Each cerebellar region is a corticonuclear microcomplex model developed previously [6].

The model of TH consists of two regions, ventral lateral nucleus connecting M1 and ventral medial nucleus connecting with S1, respectively. The individual thalamic nucleus has excitatory and inhibitory zones that receive inputs from the cerebellum and basal ganglia.

2.1.2 Inter-regional connections

Inter-regional connections are set as topographic connections between two neural sheets. Major pathways are M1 L5A to BG Striatum, S1 L5A to BG Striatum, BG GPi/SNr to Th, M1 L5B to Cb Pons, S1 L5B to Pons, Cb deep cerebellar nucleus to Th, M1 L6 to Th, S1 L6 to Th, Th to L2/3 M1, and Th to L4 S1.

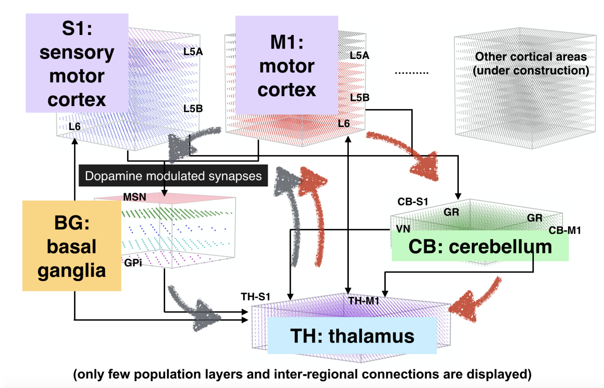

Figure 1. Network structure of the CBCT model

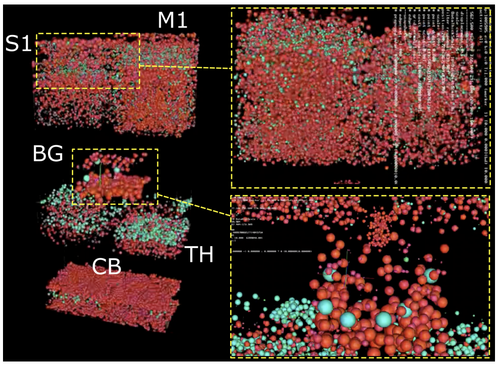

Figure 2. Neural activity of the CBCT model

Table 1. Summary statistics of the 1mm by 1mm unit of the CBCT model

Category	Region	#Neuron	#Layers	#Neuron types
Ctx	M1	58,805	5	19
	S1	94,396	7	21
TH	VL	8,192	2	4
	VM	8,192	2	4
BG	-	10,976	5	5
CB	M1	414,720	6	6
	S1	414,720	6	6
Total	-	1,010,001	33	65

2.2 Computational environment

We use the NEST spiking neural network simulator [2] that runs on CPU clusters with hybrid parallelization using OpenMP and MPI. In the scaling test, we used the K-computer [3]. We used HOKUSAI in RIKEN and Sango in OIST as well for parameter search and visualization.

3 Results

3.1 Resting-state activity

Reproducing resting-state neural activity is a first step for reproducing functions of the brain. We adjusted the levels of Poisson noise or constant current inputs so that mean population firing rates of individual neuron types reproduce physiological data (Fig. 3). In S1, M1, and TH, the neurons showed low-rate and irregular firing. The neurons of layers 5 and 6 in S1 generated gamma oscillation around 40 Hz. GPe and GPi/SNr in BG showed high-rate firing while others were low. In CB, Purkinje cells exhibited regular firing patterns, whereas granule cells emitted spikes only sparsely. No oscillatory activity was observed in the granular layer.

3.2 Scaling performance

We tested the scaling performance of the CBCT model on the K-computer. In a strong scaling test where model size is fixed, the elapsed time decreased with an increase in the numbers of compute nodes (Fig. 4A). In a weak scaling test where model size per compute node was kept constant, the elapsed times increased with an increase in the number of compute nodes, which suggests data representation issue (Fig. 4B). The largest scale of simulation was 51 million neurons, comparable to half of the mouse brain.

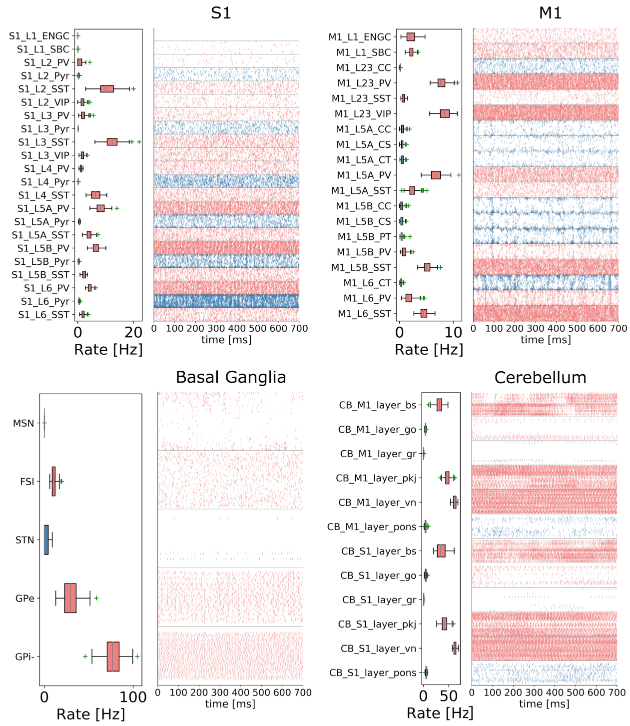

Figure 3. Resting-state of the CBCT circuit, spike rasters (right) and mean firing rate (left) per neuron types.

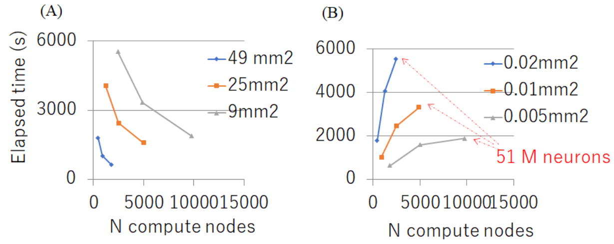

Figure 4. Scaling performance test on the K computer. (A) Strong scaling. (B) Weak scaling.

4 Discussion

We developed a CBCT model and reproduced the resting-state activity. By scaling tests on K-computer, we identified issues in scaling on even highly parallel Fugaku computer, which promoted developments of NEST 3 and our new simulator MONET [4]. The CBCT model will be a platform for further investigation of brain functions.

Acknowledgments

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