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A whole-brain spiking neural network model linking basal ganglia, cerebellum, cortex and thalamus

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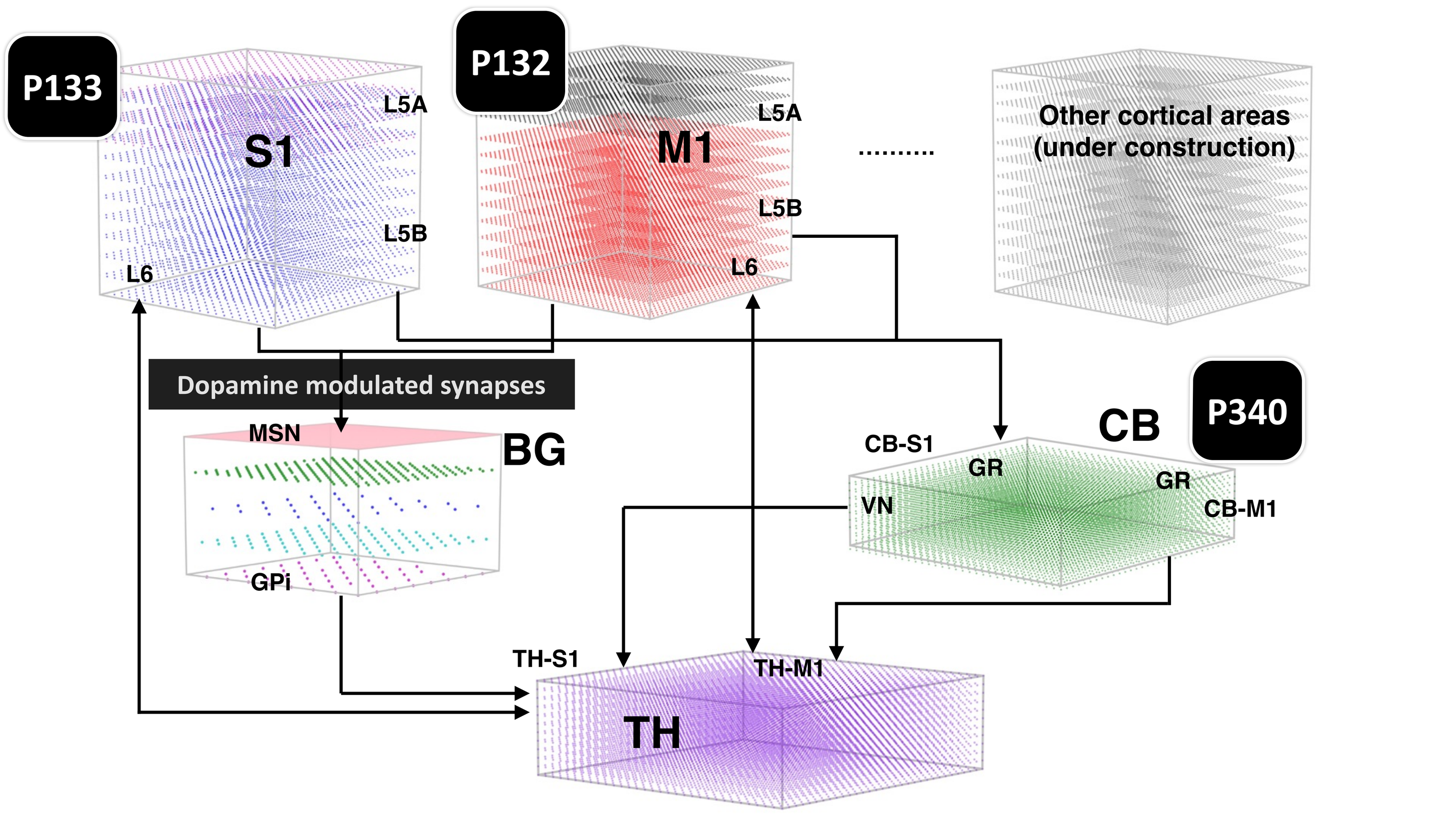
Introduction

In order to investigate the dynamic nature of the whole-brain network, we built biologically constrained spiking neural network models of the basal ganglia [1,2,3], cerebellum, thalamus, and the cortex [4,5] and ran an integrated simulation using K supercomputer [8] using NEST 2.16.0 [6,7,9].

S1: Sensory Motor cortex, **M1**: Motor cortex, **BG**: Basal ganglia, **TH**: Thalamus, and **CB**: Cerebellum.

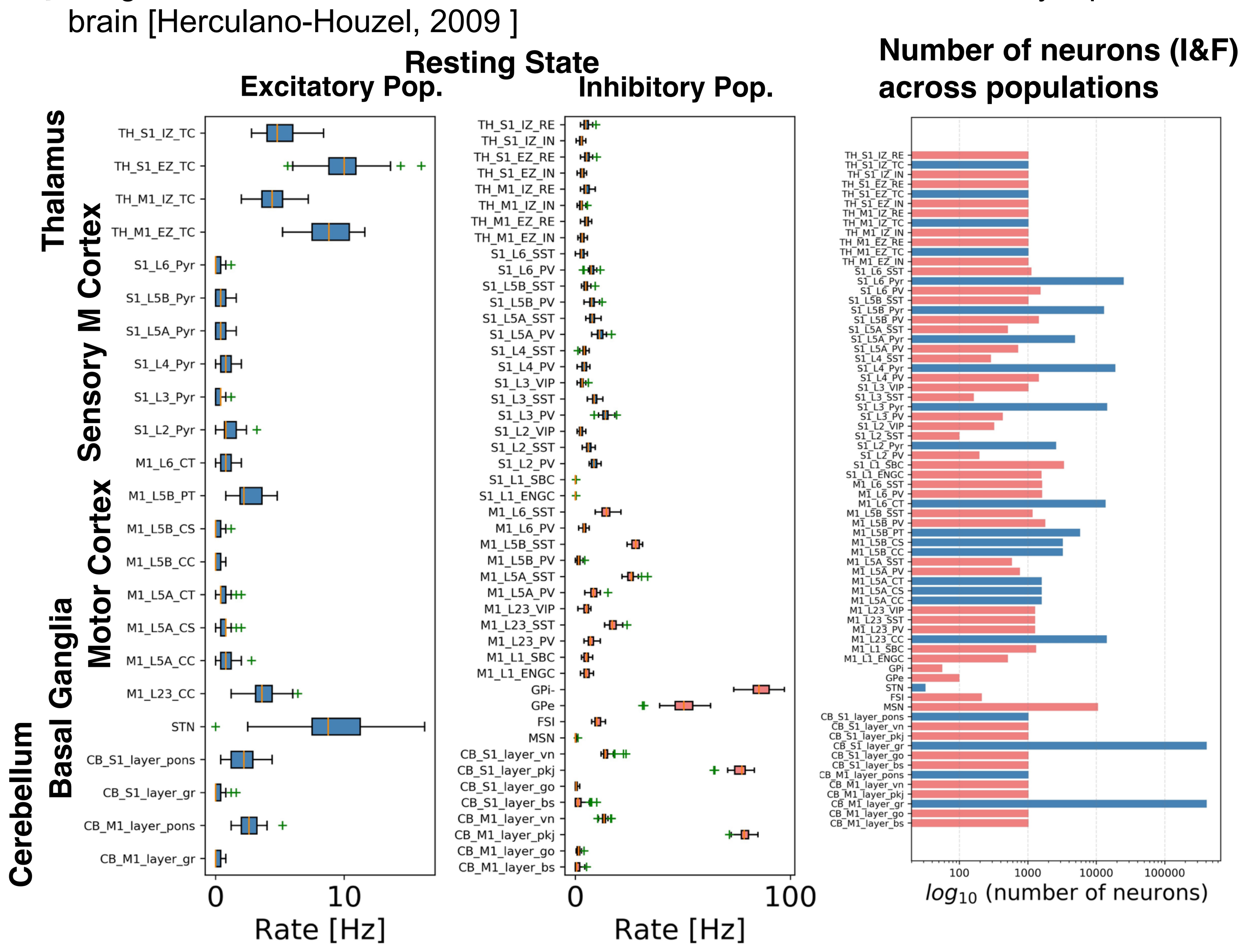


Graphical outline of the whole brain integrated model (only few population layers and inter-regional connections are displayed)

Resting State Simulations on K computer

We replicated resting state activities of 2.5 biological seconds of time in models with increasing scales, from 1x1mm^2 to 7x7mm^2 of cortical surface, and observed plausible values of excitatory and inhibitory populations firing rates.

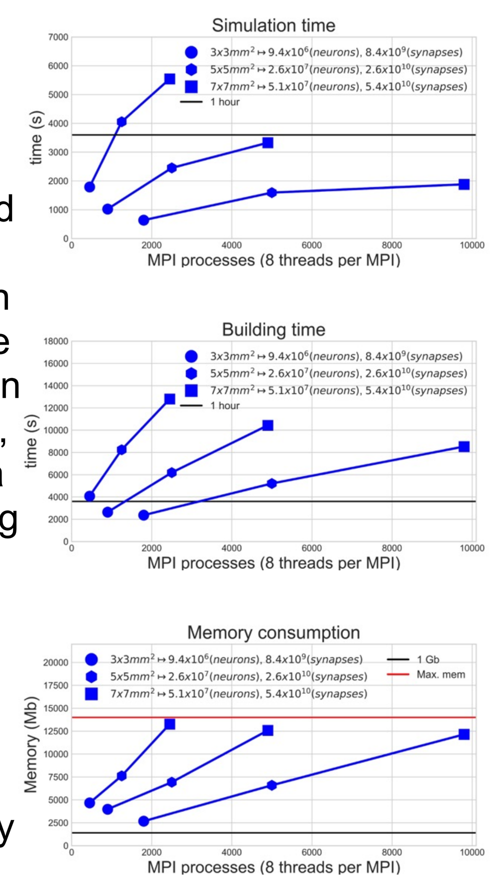
Largest simulated model includes 51 million neurons and 54 billion synapses, more than an entire hemisphere of a mouse brain [Herculano-Houzel, 2009]



To our knowledge, this is the first time a whole-brain model, of such size, implements interactions between regions such as cortico-cerebello-thalamo-cortical & cortico-basal ganglia-thalamo-cortical loops.

Simulation Performance

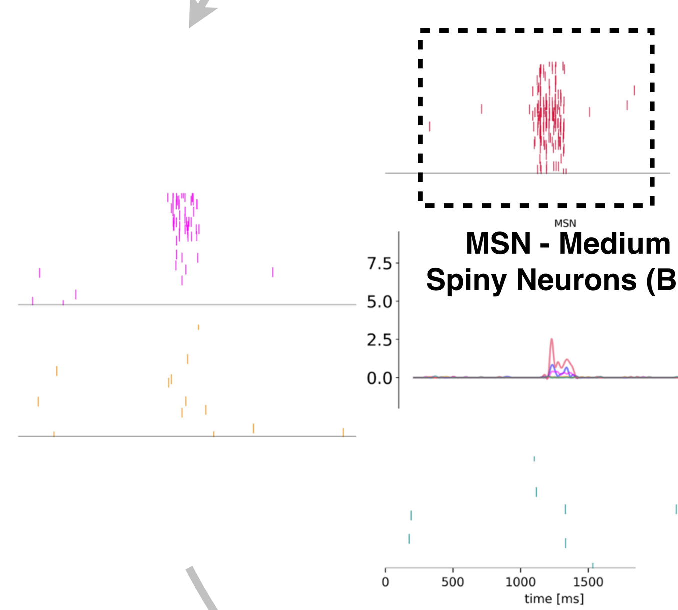
Simulations using a hybrid parallelization approach showed a good weak scaling performance in simulation time lasting between 15-30 minutes, but identified a problem of long time (between 1-3 hours) required for network building, reaching the limit of memory consumption

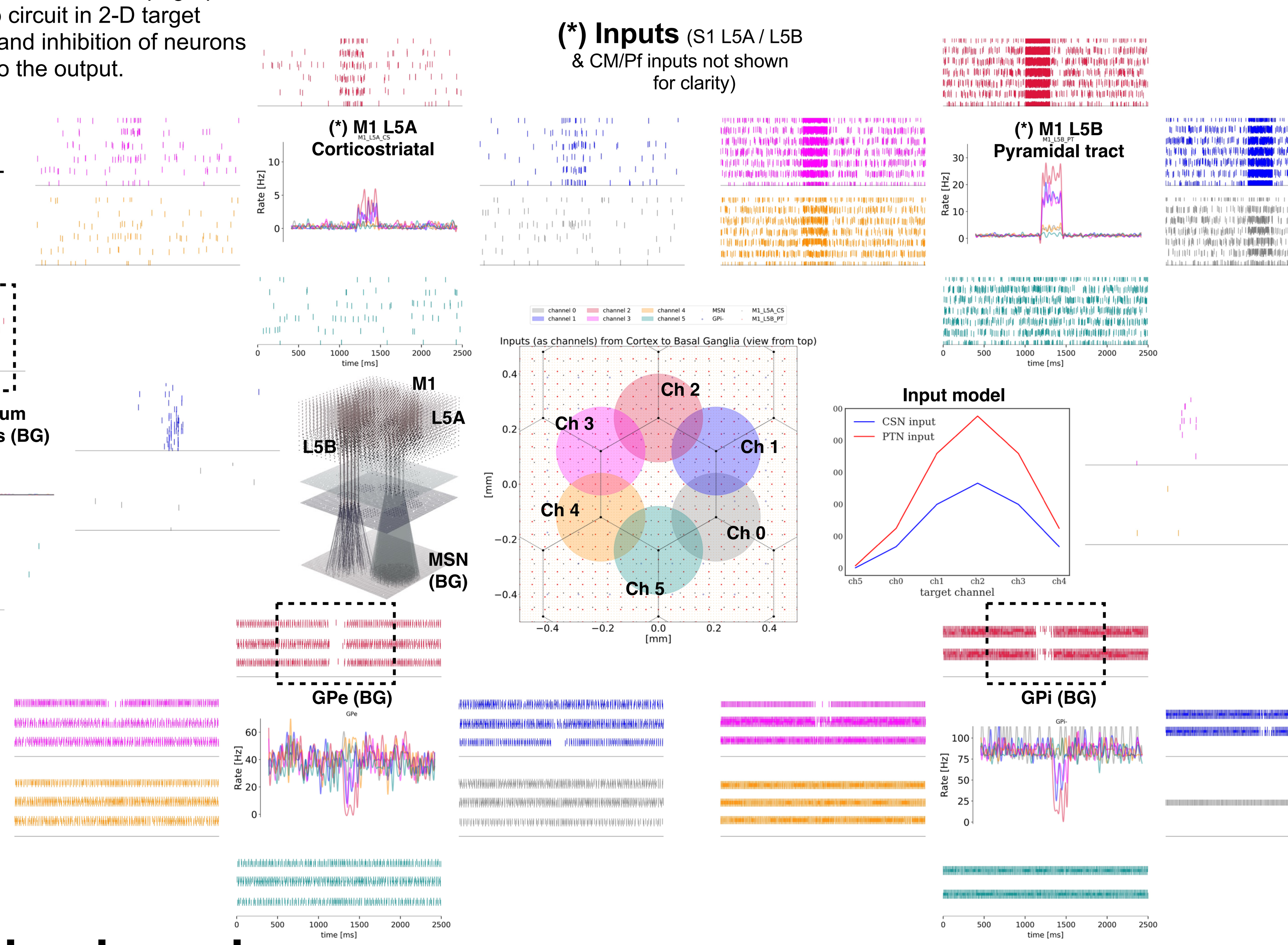


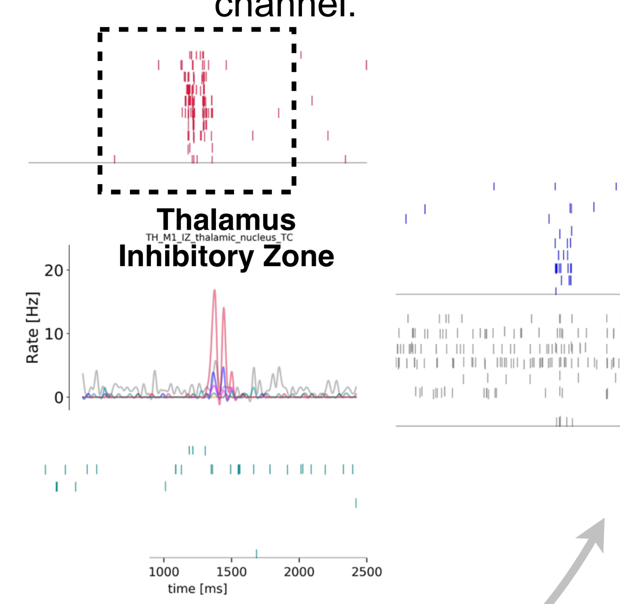
Arm-reaching task on cortico-basal ganglia-thalamo-cortical closed loop

We evaluated the properties of action selection with realistic topographic connections in the CTX-BG-TH-CTX closed loop circuit in 2-D target reaching task and observed selective activation and inhibition of neurons in preferred directions in every nucleus leading to the output.

6 circular information "channels" of 160 mu radius with some overlap are generated by a simultaneous activation of M1 L5A-L5B, S1 L5A-L5B and TH CM/Pf.







The lowest GPi activity triggers the highest activity at the thalamic nucleus inhibitory zone, providing feedback to cortex for the corresponding channel.

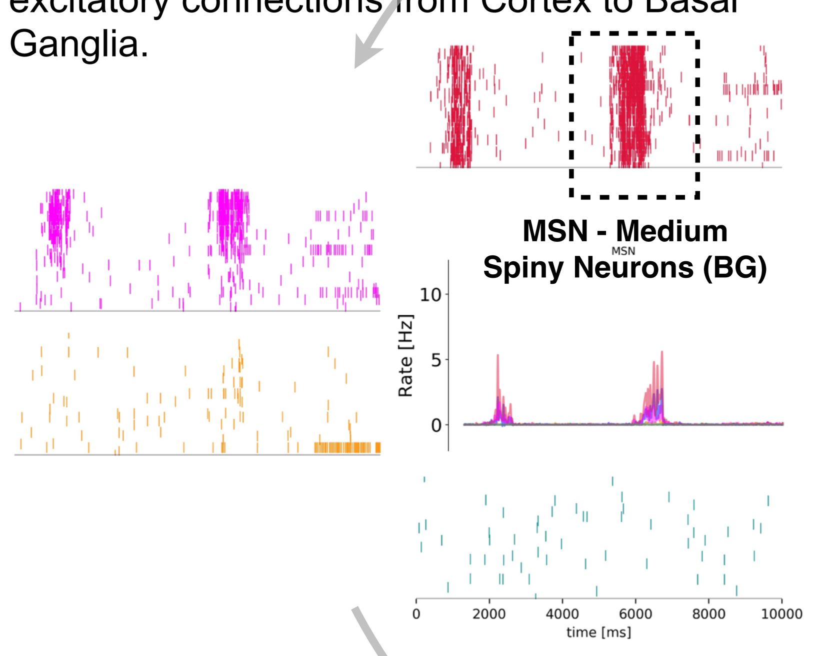
We modelled cortical activity similar to the one observed in arm-reaching tasks [10]. Firing rates of different channels are related to the direction to reach. Preferred direction is 90˚(channel 2) for this example, M1 and S1 provides the maximum firing rate amplitude to channel 2, while others channels receive lower inputs. CM/Pf provides same input to all channels.

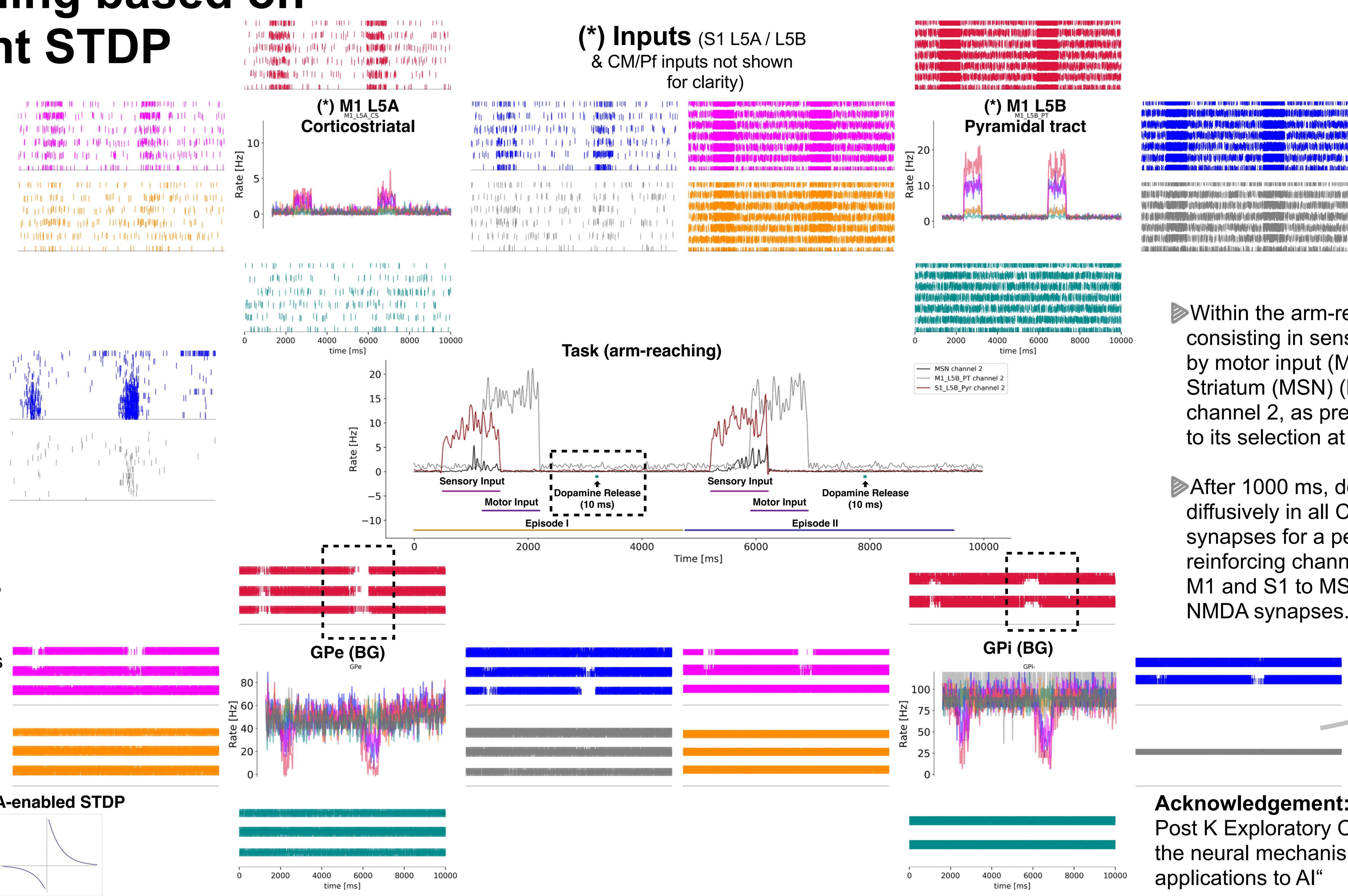
The lowest GPi activity shows the selection of the preferred direction channel. Low activity is also observed in the neighbouring channels (competitors channels).

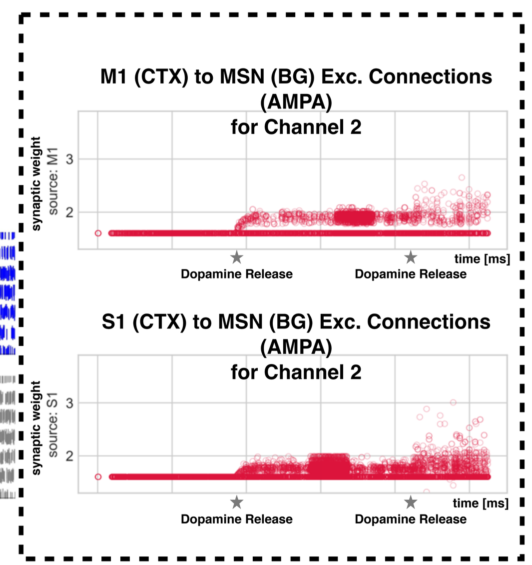
Reinforcement learning based on dopamine-dependent STDP

We performed tests of reinforcement learning based on dopamine-dependent STDP (spike-timing dependent synaptic plasticity).

We incorporated STDP [Izhikevich 2007, Potjans et. al, 2010] at NMDA and AMPA excitatory connections from Cortex to Basal Ganglia.



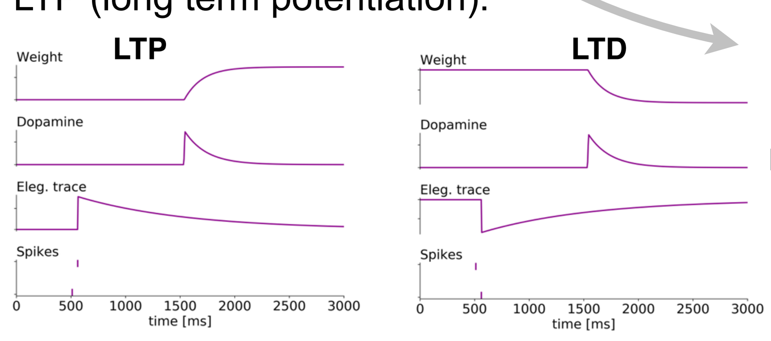




Within the arm-reaching task, an episode consisting in sensory input (S1) followed by motor input (M1) triggers activity at Striatum (MSN) (highest activity at channel 2, as previous example, leading to its selection at GPi).

After 1000 ms, dopamine is released diffusively in all CTX-MSN excitatory synapses for a period of 10 ms, reinforcing channel 2 selection by LTP of M1 and S1 to MSN (BG) AMPA and NMDA synapses.

Given an inter-spike time, the eligibility trace and dopamine concentration dynamics governs the synaptic LTD (long term depression) and LTP (long term potentiation).



DA-enabled STDP

Future work: further investigate closed loops dynamics. Implement reinforcement learning using D1 and D2 MSN and integration of a virtual/robotic arm. Test model scaling using plastic synapses. Model preparation for Fugaku supercomputer.

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