NeuroViz: Visual Analytics of Neural Behavior in Temporal Plasticity Changes

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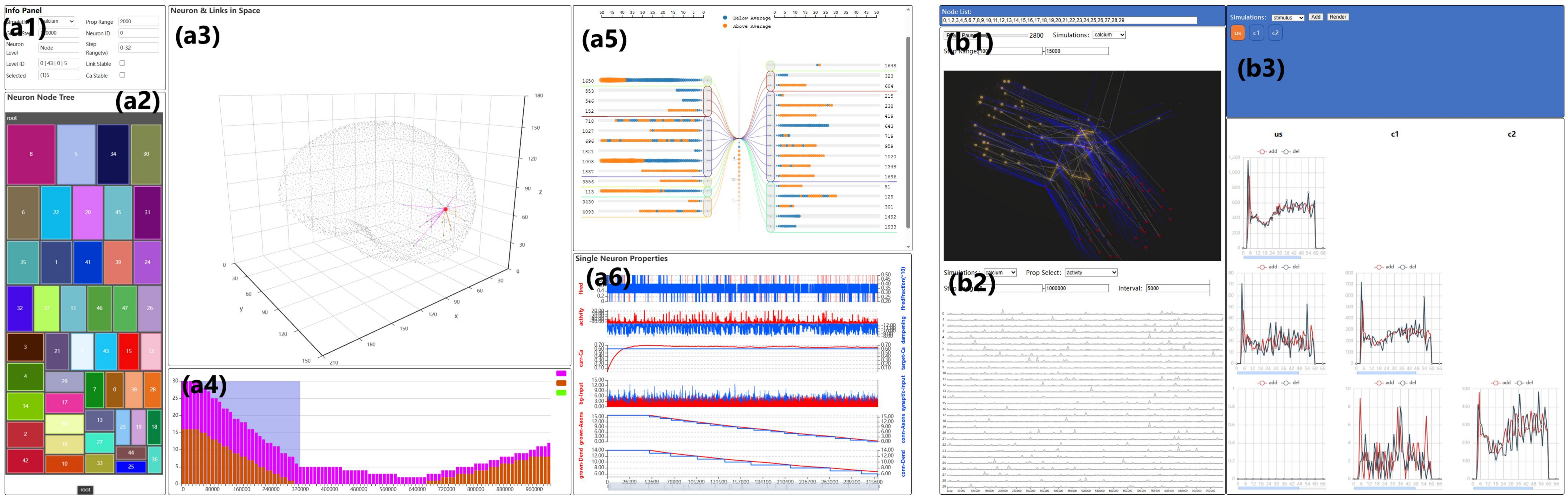

Figure 1. System overview. NeuroViz is divided into two parts: The left side is the node analysis part, which is used to visualize the structure and attribute status of a single node in sequence. On the right is the graph analysis part, which is used to disassemble and display the subnets of interest to users in the overall network, and supports correlation analysis of multiple subnets

Method

Neuron steady state

Neuron is the basic unit of nerve signal transmission, through the growth of axons and dendrites, nerve conduction to the surrounding neurons in the form of ionic electrical signals. For each neuron, we make two criteria on whether it enters homeostasis according to the changes in its synaptic connections with other neurons. The two criteria contain the difference between calcium concentration and target calcium concentration and a criterion for determining synaptic connection homeostasis. Specifically, this concept is similar to variance: the synaptic change variance, which is calculated as follows.

$$V_j = \frac{1}{N}\Sigma^i d_i \Delta\omega_i$$

where i is all neurons connected to j, d_i is the physical distance between each neuron connected to j, N is the number of all neurons connected to j, ω_i is the weight of each neuron connected to j, and $\Delta\omega_i$ represents the difference in continuous time step.

Average minimum cluster spacing

We call a cluster of 10 neurons a "cluster." The average minimum cluster distance is used to describe the average distance between adjacent clusters of each cluster in the entire brain space. The average minimum cluster spacing is calculated as follows:

- For each cluster C, consider all other clusters as its adjacent cluster D.
- For each adjacent cluster E_i, if there is another adjacent cluster E_j and $\cos \angle E_i E_j C < 0.5$, E_i is deleted.
- Calculate the spatial distance between the cluster and all its adjacent clusters, and take the average D_i.
- Calculate the mean of the adjacent cluster distance of all clusters as the average minimum cluster distance of the whole brain region.

Introduction

Modeling of neuronal networks and simulating changes in calcium concentrations enable the analysis of the variations in brain function and neuronal connections. However, simulations involve modeling thousands of neurons and generating substantial temporal data throughout the simulation process. The processing and analysis of such massive data sets pose challenges in comprehending their information.

To address these challenges, we designed a visual analytics system that facilitates experts in comprehending the associations between neuronal connections, calcium ion concentration changes, and brain functionality through visual analysis of temporal plasticity in neural behavior. These visual tools enable researchers to delve deeper into the intrinsic information of the data.

Visualization

- Info Panel (a1) view supports choosing different simulation themes, simulation steps, neuron IDs, node hierarchy levels, and more.
- Neuron Node Tree (a2) view stores and retrieves all neuron data in a three-level hierarchy of brain regions, clusters, and neuron nodes.
- Neuron and Links in Space (a3) view displays all neurons based on their positions.
- A stacked bar chart (a4) provides statistics on the number of relevant connections.
- Neuron Links Information (a5) view presents the connection information of the selected neuron.
- Single Neuron Properties (a6) view presents multiple line graphs showing the variations of selected neuron's attribute values over simulation time steps.
- 3D relationship view (b1) is used to visualize the association of an independent sub-graph.
- Multiple area charts (b2) are used to display a specified attribute of all nodes in a sub-graph.
- Statistical matrix view (b3) is used to analyze the correlation between multiple sub-graphs.

Result

Case 1: Steady State-Based Evolution of Connectivity and Attributes

As shown in Figure 2, when the current calcium concentration has not reached the target concentration, neurons rapidly generate new axons and dendrites, and increase their connections with external neurons. Generally, during the early stage of axon and dendrite generation (Figure 2a), generation and connection events occur simultaneously. In the later stages of generation, most connections are established through dendrites, resulting in some excess axons not being connected. Once a steady state is formed, with the current calcium concentration fluctuating within a small range around the target concentration, the number of axons and dendrites remains constant, with only minor changes in the connections with external neurons (Figure 2b). If the current calcium concentration exceeds the target concentration, neurons proactively remove a significant number of connection events and drastically reduce the number of axons to significantly lower the current calcium concentration (Figure 2c).

Case 2: Disable analysis by comparison

We calculated the change of calcium ion concentration in neurons under each classification on the disable simulation and the stimulus simulation. The statistical results shows that the number and distance of disabled neurons around them have little effect on their reaching the target state, active neurons in the periphery quickly feed back to maintain themselves.

We further analyze neurons connected to deactivated neurons within the system in Figure 3a. It is evident that at step 100,000, neuron 5 loses its connection with the deactivated neuron. Neuron 5 rapidly establishes connections with other neurons to reach the target calcium concentration. Figure.3(b) depicts the evolution of neuron 5 during a stimulus simulation, showing no significant differences compared to Figure.3(a).

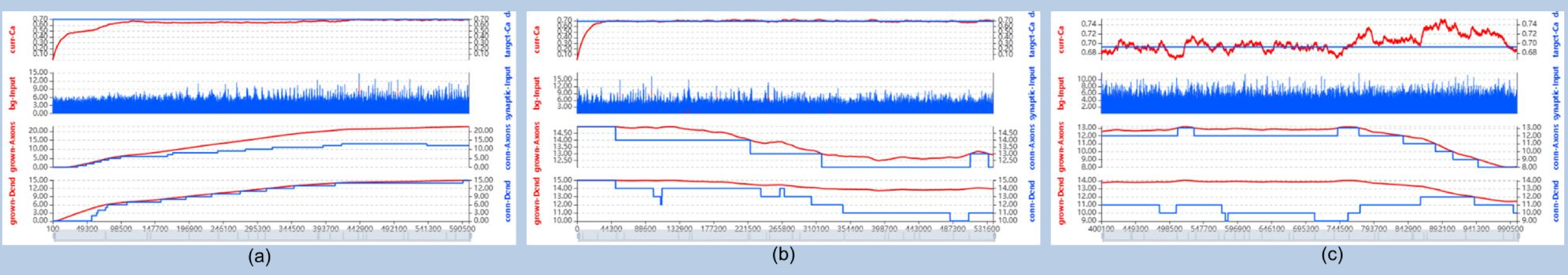

Figure 2. The evolution of calcium ion concentration, axon and dendrite generation, and connectivity in neurons. (a) Neuronal generation of axons and dendrites and establishment of connections leading to steady state. (b) Evolution of neurons during the steady state period. (c) Evolution of neurons during the fluctuation of current calcium concentration in the steady state period.

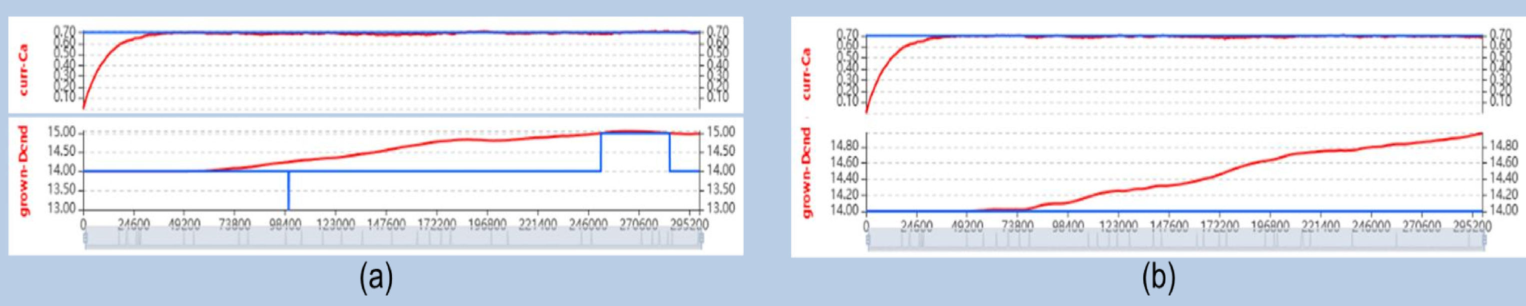

Figure 3. The changes in calciumion concentration and dendritic connectivity of neuron 5 during the disable simulation (a) and stimulus simulation (b).

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