University of Amsterdam

Scientific Visualization and Virtual Reality

Visualising the Brain

A Custom Tool for Investigating Lesion and Stimulation Dynamics in the Human Brain

As part of the program
MSc Computational Science

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Abstract

I don't like this part so you do it **Battagl!n!-F!scher**

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Contents

1 Introduction

In this paper we propose a custom visualisation experience for brain data aimed at a scientific audience. Our software is based on VTK [1] and written from the ground up in a web framework. It enables researches to specifically analyse brain activity according to the *Model of Structural Plasticity* [2]. To demonstrate its value as a scientific tool, we use our framework to investigate the plasticity in the brain and the effects of stimulating or damaging certain neuronal areas. The test dataset for this, provided by the 2023 IEEE SciVis Contest [3], includes simulations of human brain activity, accompanied by values for a range of metrics per time step.

This allows a broad exploration of neuronal network properties and dynamics under various conditions. As a test case, we research how applying external stimulation to certain areas leads to lasting changes in connectivity and firing patterns, and investigate if the connections between these areas is consistently stronger. Furthermore, we examine how the network reorganizes when certain neurons are disabled, questioning whether previously connected neurons rewire to preserve overall network activity. Ultimately, we aim to provide a tool that deepens the understanding of the brain data and the underlying processes of structural plasticity in the human brain.

2 Theoretical Background

2.1 Brain Plasticity

Neuroplasticity, also known as brain plasticity, describes the brain's ability to reorganise its structure, functions, or connections, enabling adaptation to stimuli and injuries from internal or external sources [4]. It can be categorized into two major types: *Structural neuroplasticity* and *Functional neuroplasticity*. This report will mainly focus on the first type; for a deeper understanding of the latter, refer to [5].

Structural neuroplasticity refers to the physical changes in the brain's structure, meaning modifications in the neural network, such as creation, elimination, and strengthening of connections between neurons. Two main concepts in structural neuroplasticity are *Synaptic Plasticity* and *neurogenesis*:

- *Synaptic Plasticity* is defined as the strengthening or weakening of synapses, the connections between neurons. As the structure adapts, the changes occur in the size, shape, and number of synapses, often originated by neuronal activity. Dendrites form and retract spines (small extensions of the membrane where synapses form), while axons create or adjust connections to facilitate communication.
- *Neurogenesis* is defined as the process of generating new neurons, specially in specific regions such as the hippocampus. New neurons grow axons and dendrites, integrating into existing networks and contributing to learning, memory, and recovery.

Additionally, *Calcium* plays a key role in the aforementioned processes by acting as a signalling molecule [6]. At synapses, calcium influx regulates the strengthening or weakening of connections by modulating receptor activity and triggering pathways for dendritic growth or retraction. In axonal growth, calcium guides the direction and branching of growth cones, enabling the formation of new connections. Accordingly, during neurogenesis, calcium also plays an important role in generating new neurons. Notably, given the nature of the Brain dataset (3) used in this research, this report will only focus on synaptic plasticity.

2.2 Brodmann Areas

Brodmann areas are a system of numbering regions of the cerebral cortex defined in the early 20th century by Korbinian Brodmann. These areas were distinguished according to differences in neuronal density, layering, and cellular morphology [7], identifying 52 different areas in the human brain. Furthermore, additional research correlated each Brodmann area with a distinct functional specialization such as sensory processing, language comprehension, or executive functions. These are shown in 1.

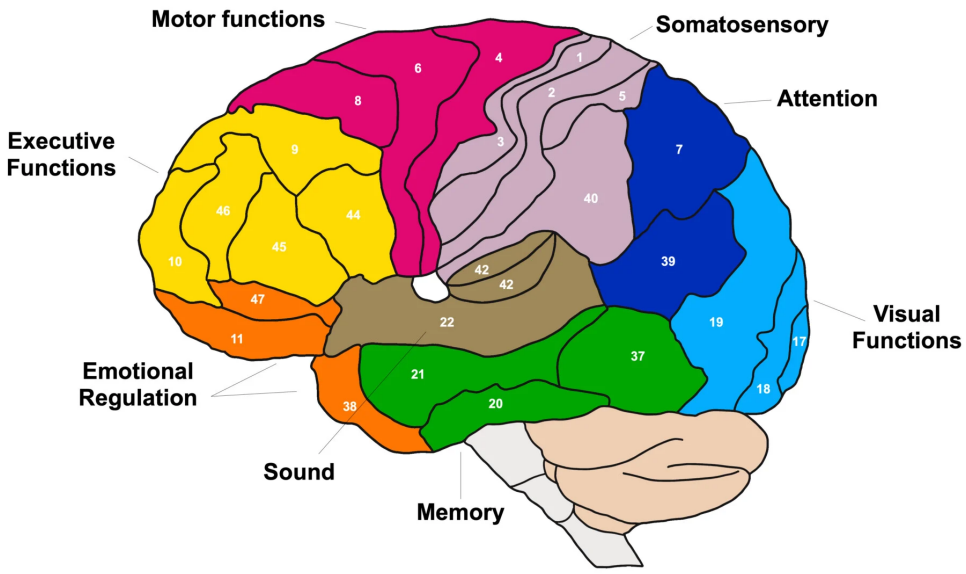


Figure 1: Brodmann Areas of the brain (Left view): Anatomy and respective functions

3 Methods

3.1 Dataset

The simulation covers a network of 50.000 neurons per ensemble, across four ensemble members, encompassing approximately 50GB of data. Each neuron is represented by a node with properties such as 3D location, current calcium level, target calcium level, and electrical activity [3].

The dataset includes detailed information about neuronal axons (outgoing connections) and dendrites (incoming connections), which form synapses. When a neuron fires, its calcium level increases only to decrease again over time. Neurons aim to reach a certain target calcium concentration based on their current calcium level. To achieve this, it either seeks to increase or decrease the level of incoming electrical activity resulting in the addition or removal of elements, which, in turn, leads to the formation, rewiring, or deletion of synapses.

This dataset encompasses four simulations conducted under different conditions, where each simulation runs for 1,000,000 steps, with data sampled every 100 steps [3]:

- **No-Network Simulation**: Initial state with no connections between neurons. All neurons start with equal target calcium levels and no existing synaptic connections.
- **Lesion Simulation** (*"Disable simulation"*): Starts from the results of the first simulation. Simulates the impact of neuronal damage by deactivating 10% of the neurons, modelling the effects of injuries or neurological damage.
- **Learning Simulation** (*"Stimulus simulation"*): Builds on the first simulation. Introduces targeted electric stimulation in specific areas to simulate learning effects and how neuronal networks adapt under stimulation.
- **Calcium Variation Simulation:** Also derived from the first simulation. Assigns several target calcium levels to neurons, modelling differences in neuronal excitability and activity regulation.

3.2 Data Processing

Our primary goal while developing this visualization tool was to illustrate brain activity at each timestep for all four scenarios — No-network, Lesion, Learning, and Calcium. Given the size of the dataset ($\approx$ 50GB),

loading every neuron file for each simulation timestep proved to be computationally intensive. Therefore, we limited the visualization tool to display data at intervals of 10,000 up to 1,000,000 timesteps.

Additionally, we organized neurons and their corresponding connections based on identified brain regions. By mapping each neurons 3D coordinates to specific areas and correlating them with established areas of the brain, we aim to provide a meaningful anatomical context for the observed activity and a more manageable representation of the dataset.

The processed data was then exported as VTP files. This format ensures compatibility with standard visualization frameworks built upon VTK, allowing for an efficient visualisation that presents the neural network and activity patterns in an interactive and useful manner. This data was enhanced with auxiliary files that provide context on the scientific background.

3.3 Our visualisation tool

To enable the effective visualisation of such an extensive dataset, we designed and developed a custom application. While a simple visualisation in Paraview would have sufficed for this data, a custom setup has several advantages:

- *It is lightweight.* Large, corporate software packages can be very clunky, require installation of many packages etc. Paraview is known to be buggy and not very user friendly.
- *It is tailored to the task and the domain.* Domain scientists don't want to spend time learning software cluttered with features not useful for the task. A custom setup with specialised, easy to use tools
- *It is easily extendible.* Anyone who requires additional functionality can add it. We have a modular setup that utilises the extensive VTK framework [], which is well known, powerful and maintained.
- *It has a larger didactic effect.* The best way to learn scientific visualisation is to build one from the ground up, just using the tools of already written software.
- *It is easily distributable.* Our tool can easily be deployed on the web for anybody to use.

In consequence, these points create a list of functional requirements for our visualisation tool.

3.3.1 Design process

To cater to these requirements, we designed an interface suitable for the task - visualising a dataset of the brain. For this, we decided we need focus on an interactive main visualisation in 3D with buttons and sliders to manipulate the view according to the research focus. This should be accompanied by a section displaying the numeric results of simulations on this data, to aid the understanding and interpretation thereof.

To this end, we created a React.js web application, utilising backend functionality from VTK.js to display the visualisation. This makes our tool performant, scalable and well accessible. Specifically, we harnessed Reacts contexts and reducers. These methods effectively decouple the application states from each other and thus make the application modular (easy addition of additional tools) and performant (little to no loading times of complex datasets). It is built with developers in mind, who could add additional functionality from VTK's toolbox with minimal effort.

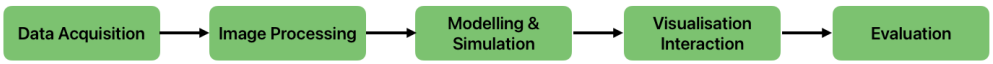


Figure 2: Conceptual medical visual analysis pipeline, from [8].

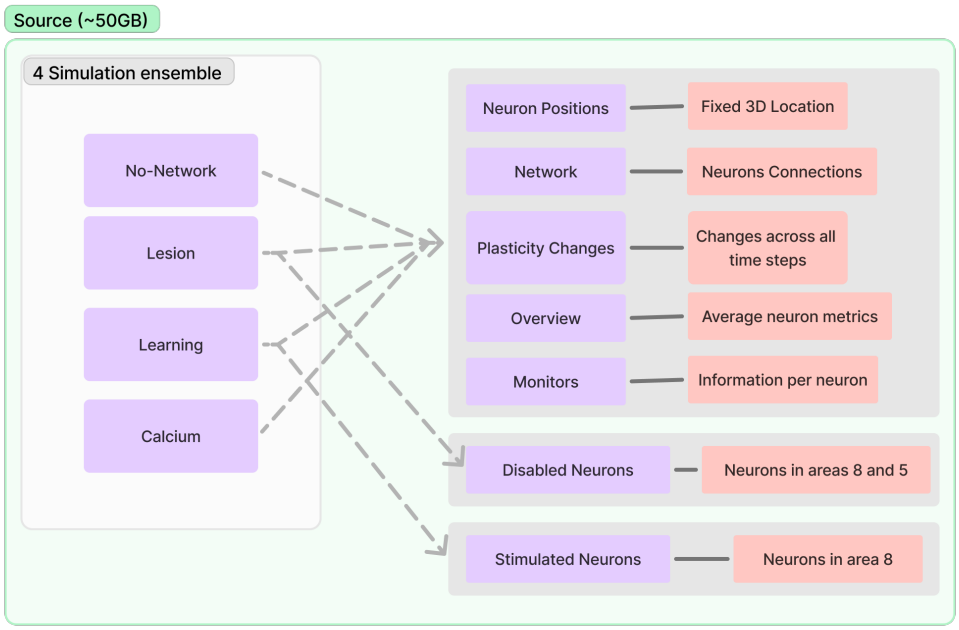


Figure 3: Data pipeline

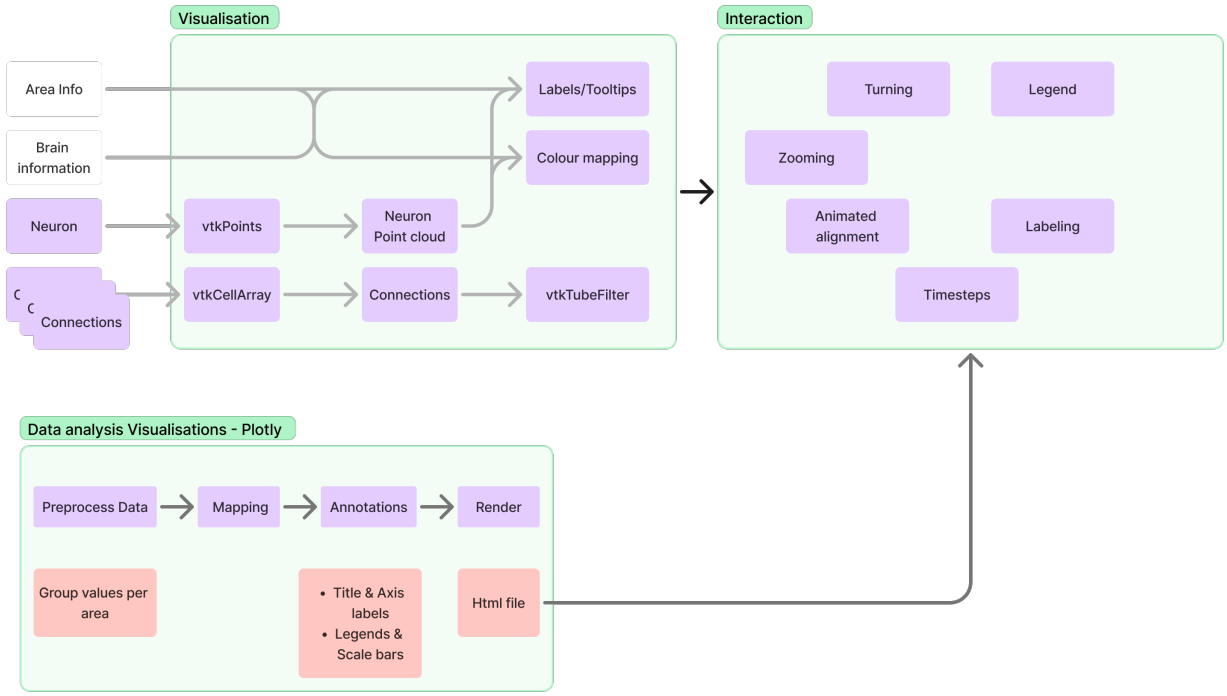


Figure 4: Visualisation pipeline

3.3.2 The main 3D viewer

The core of our application is an interactive representation of the brain, where the neurons are displayed as a point cloud and the connections as tubes between the brain areas (see fig. 5). Zoom and rotation of the object can be handled by standard mouse/trackpad gestures. This is aided by an orientation marker in the bottom corner, labelled with the correct neuroscientific terms for the different orientations of the brain (superior/inferior, left/right, anterior/posterior). Accessing these planes can be done by clicking the buttons in

the top right, that zoom to a predefined perspective with an animation that enables the viewer to see how the brain is being turned. Therefore, he doesn't lose orientation.

A legend offers insight into the mappings, and the top left corner is populated with a button that shows labels of the brain areas. On hovering over them, they display tooltips explaining information such as functional properties and values associated with the current selected simulation (see fig. 6). The selection and timestep progression controls are located in a separate sidebar, completing a clean interface.

3.3.3 Data analysis Visualisations

To complement our 3D visualizations and gain a deeper understanding of the brain's adaptive capacity, we also added a series of 2D plots using the Plotly library, dynamically integrated into our interface. These plots enable a closer view of temporal trends and structural changes, highlighting patterns in number of synapses, firing rates, or connectivity shifts as specific neuronal areas are stimulated or disabled. By presenting the data in a simplified two-dimensional format, we can more easily identify significant changes, steady-state behaviours, and emergent properties of the network. The user can thus scroll between the two views and analyse aspects from a general or analytical perspective, as needed.

4 Results

4.1 The resulting tool

Exemplary screenshots from our tool can be seen in figures 5 and 6. For a video demo see the folder provided.

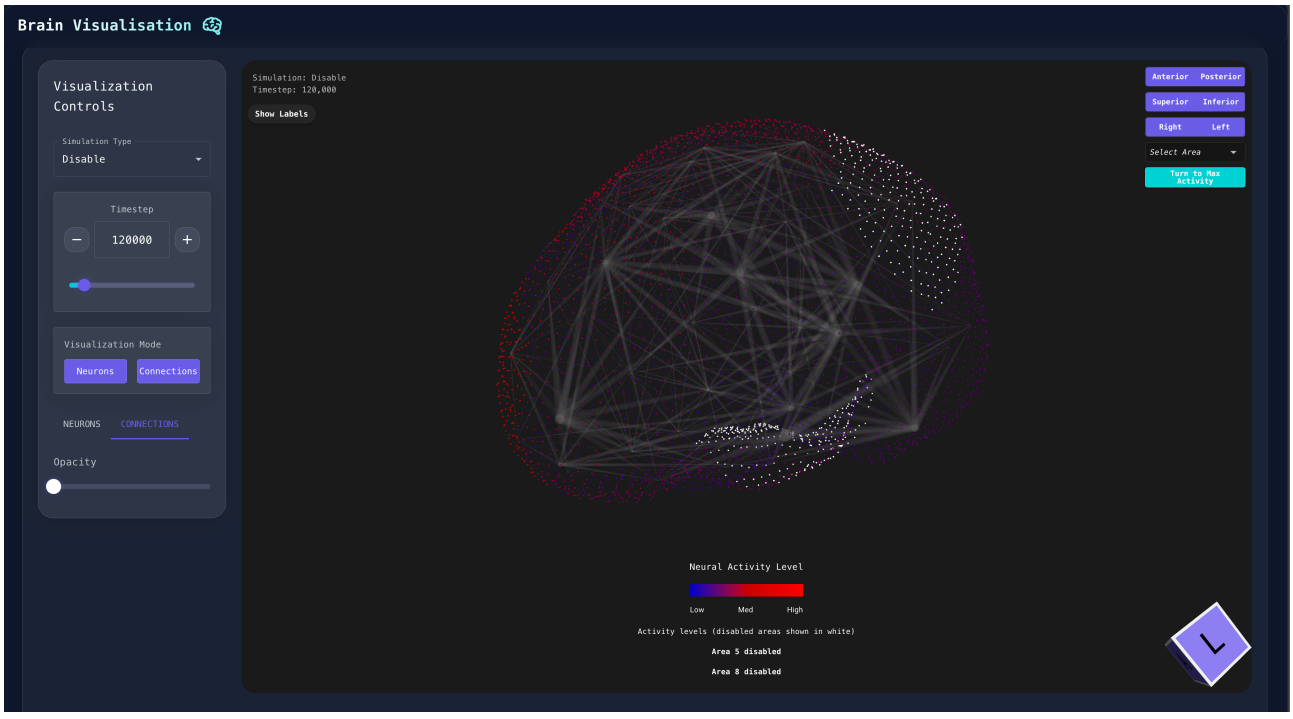


Figure 5: Main interactive visualisation of the *Lesion simulation*. The opacity of the connections is turned down. We have the option to show labels in the top left with basic information about the currently selected simulation. The top right corner has buttons to automatically align the visualisation to find a certain area or view it from a certain angle, which can be identified by the vtkOrientationMarkerWidget in the bottom right. The legend at the bottom shows the neuronal activity level with an indication of which areas are disabled, that are also colored white in the visualisation. The controls on the left allow switching between simulations and timesteps, switching off the neurons or connections and adjusting the opacity.

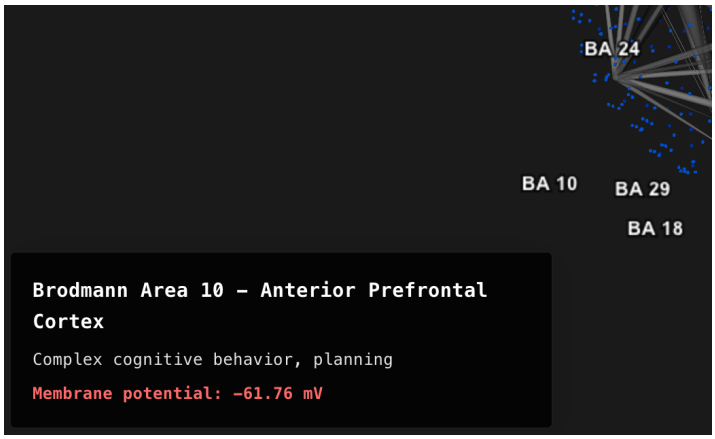
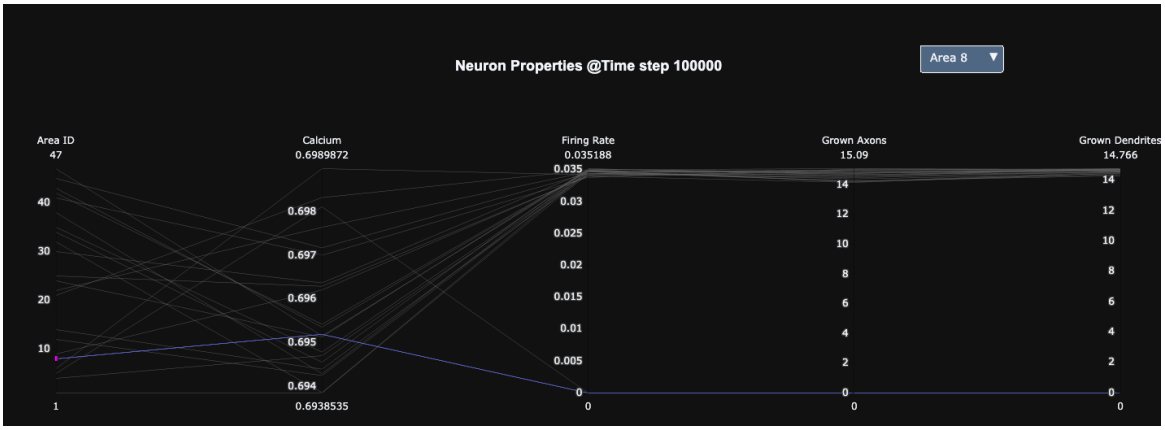


Figure 6: Informative tooltips appear in the bottom left corner, here as an example for the *Learning Simulation*. They show which Brodmann area we are looking at, including detailed information on the function of the area and the relevant numerical values.

4.1.1 Data analysis Visualisations

- **Neuron Properties Distribution** This visualization in figure 7 provides an insightful view of neuronal properties at a specific time step (1,000) across all brain areas. The upper plot shows a comparative visualisation on multiple metrics—such as calcium levels, firing rates, and the growth of axons and dendrites—linked to individual areas. By selecting a particular area from the drop-down menu, users can quickly see how that region's values align or deviate from others. The lower box plot in figure 8focuses specifically on calcium levels, enabling a direct comparison of their distributions across several areas. Together, these interactive plots offer insights into how different regions contribute to overall network dynamics.

(a) Two-dimensional connectivity analysis for the Disabled simulation at time step 40,000, visualizing how selecting Area 8 highlights variations in calcium, firing rate, axon growth, and dendrite growth across all areas.



(b) Two-dimensional connectivity analysis for the Disabled simulation at time step 100,000, showing the pronounced impact of disabling Area 8, as its values drop to zero, thereby revealing the consequences on network properties.

Figure 7: Overall comparison of two simulations at different time steps and their respective impacts on Area 8.

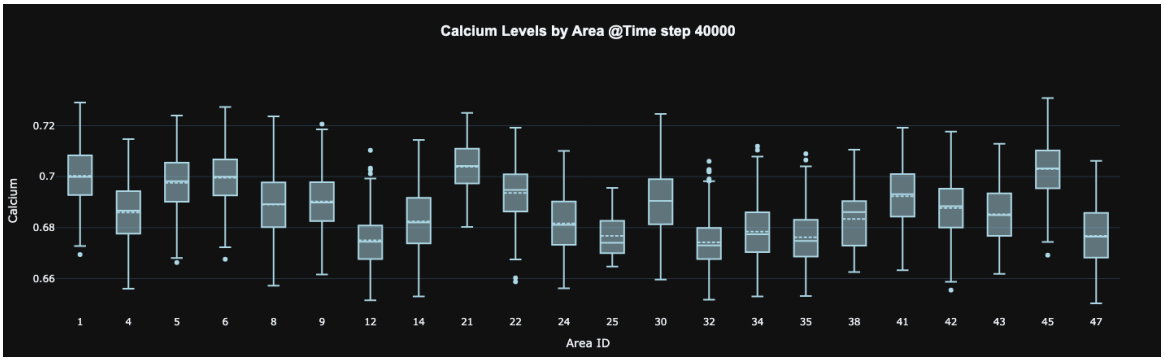


Figure 8: Calcium distribution analysis for the Disabled simulation at time step 100,000.

- **Network Connectivity Analysis**

  The interactive 2D heatmap presented in figure 9 offers a clear view of how different brain areas are connected at a specific time step. By mapping each neuron to a labelled area and aggregating synaptic counts between these areas, the resulting matrix presents the strength of inter-area connections as color-coded intensities. By hovering over individual cells, we can instantly see which areas are involved and how

strongly they are connected, as indicated by the number of synapses. The upper triangle and diagonal are masked to reduce visual clutter, making it easier to identify patterns and highlight critical connections.

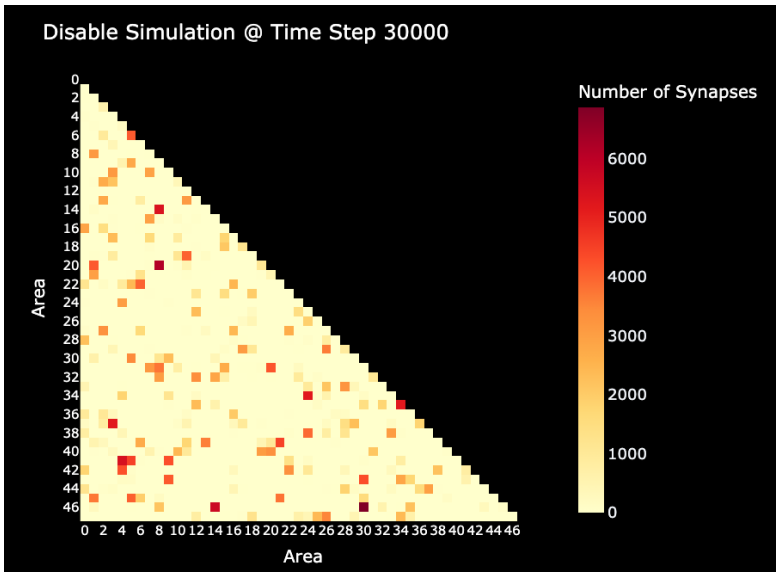
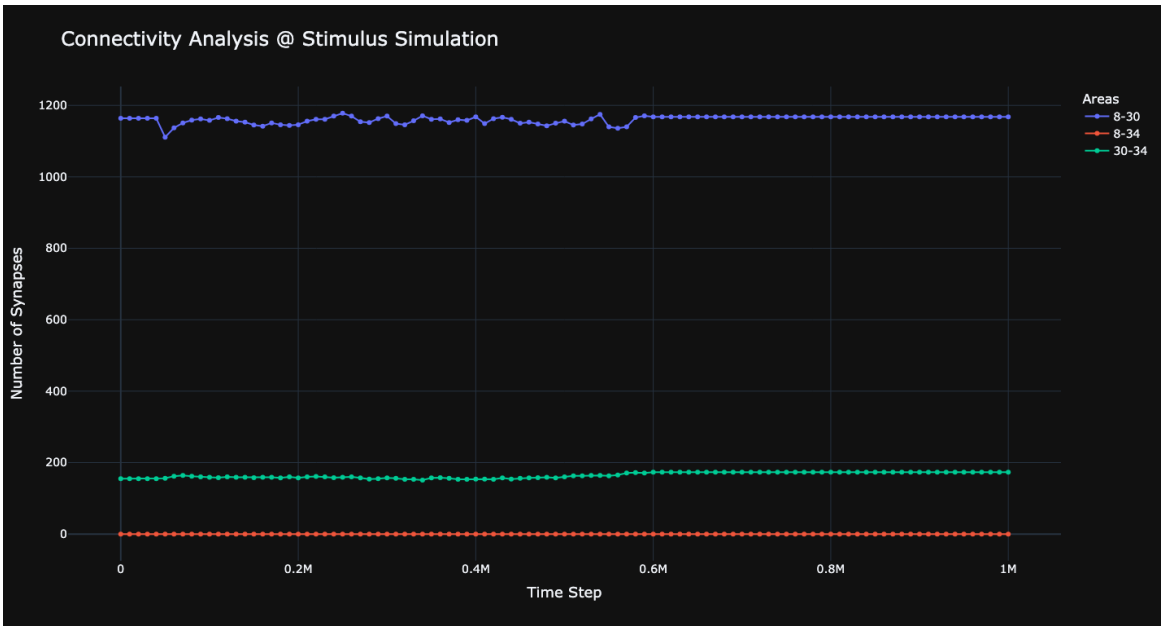
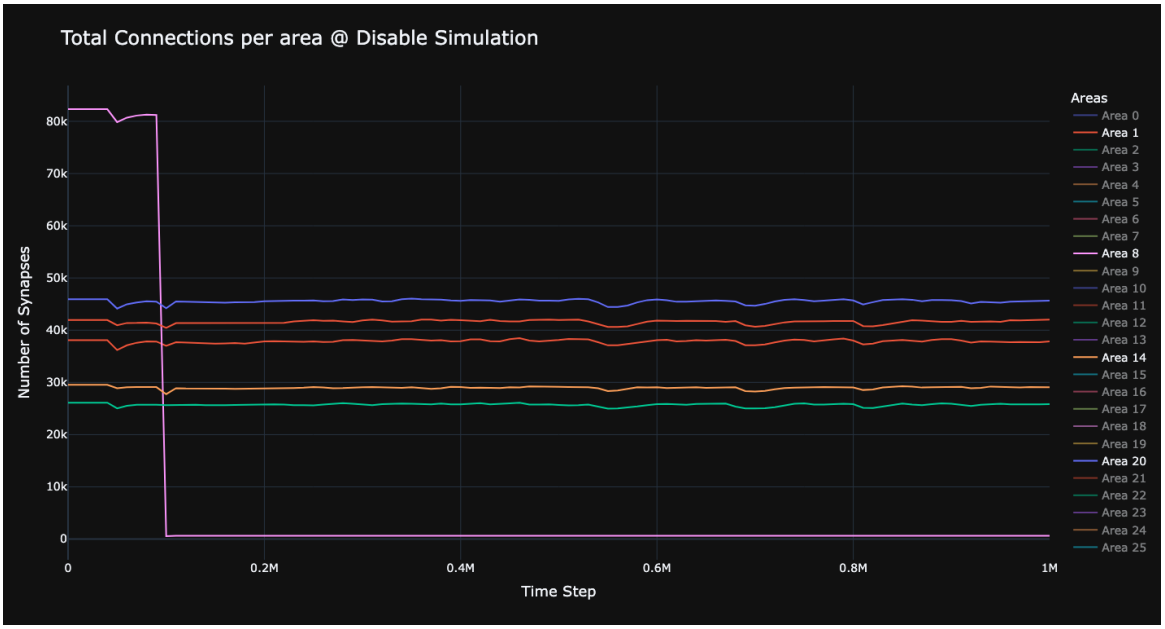


Figure 9: Interactive 2D heatmap illustrating the number of inter-area connections. The color scale on the right shows the number of synapses. By hovering over each cell, one can identify the involved areas and their corresponding connection counts. This visualization, based on the *Lesion simulation* at time step 960,000 where areas 5 and 8 were disabled, exemplifies how disabling certain regions affects connectivity.

- **Temporal Evolution** The two interactive line plots in figure 10 show how neural connectivity evolves over time under different simulation conditions. The first plot focuses on specific area pairs during the Stimulus simulation, illustrating how their connectivity strength changes as the simulation progresses. The second plot presents the total number of synapses per area in the Disabled simulation, allowing for a direct comparison of connectivity levels among multiple brain regions. Thus, when Area 8 is disabled, we observe a sudden decrease in its connectivity as well as in the connectivity of its neighbouring areas.



(a) Two-dimensional connectivity analysis for the *Stimulus* simulation, highlighting changes as Area 8 is stimulated at time step 50,000.



(b) Two-dimensional connectivity analysis for the *Disabled* simulation, highlighting changes as Area 8 is disabled at time step 50,000. The interactive functionality allows for the user to choose the neighbouring areas and analyse the impact of the simulated lesion.

Figure 10: Temporal evolution visualisations

- **General Overview** The combined 2D plots in figure 11 provide an overview of the neuron properties across the four simulation scenarios. It focuses on neuron properties, including calcium levels, axon counts, connected axons, and dendrites, along with their respective variabilities. The visualization easily allows the user to compare simulations, revealing how different conditions shape the brain's structural adaptations and functional dynamics. The interactive nature of the plot enables the user to select individual simulations on or off, allowing for a customized view.

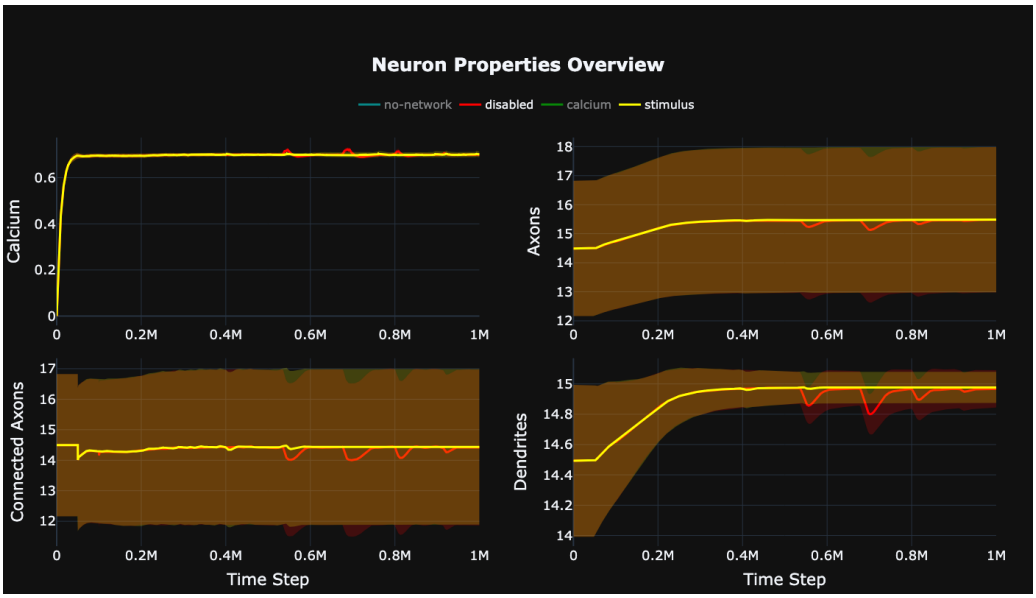


Figure 11: Neuron properties analysis over one million time steps, highlighting changes in different properties—calcium levels, axon counts, connected axons, and dendrite counts. The interactive functionality allows for the user to select individual simulations on or off, allowing for a customized view.

5 Discussion

Offering a modular and scalable approach to visualising the brain, we present a valuable tool for conducting neuroscientific research. The application is intended as a foundation and it is highly modifiable, being built in the popular web framework React, which enables researchers to extend the functionality as needed. The VTK library is vast, offering far more functionality than we could add in a short project. Additions could be VTK's extensive filters to highlight certain aspects of the data more, more animation or integration with VR capability.

As a demonstration, we were able to use our tool to show that lesions and stimulations of parts of the brain have significant impact on neuronal connectivity. The brain undergoes structural changes as a result, re-routing the paths between brain areas and paving the path for a deeper understanding of neurophysiology.

6 Conclusion and Outlook

Ultimately, this project demonstrates the potential of computational models and effective, targeted visualizations in advancing our understanding specifically of brain function and behaviour. By providing a user-friendly interface for exploring complex neural networks, our tool enables researchers to gain new insights into the intricate relationships between neurons, synapses, and brain regions. As a continuation, our application could easily be deployed to the web and used by researchers and students.

References

[1] VTK - The Visualization Toolkit, December 2024. URL https://vtk.org. [Online; accessed 13. Dec. 2024].

[2] Markus Butz-Ostendorf and Arjen Ooyen. *A Detailed Model of Homeostatic Structural Plasticity Based on Dendritic Spine and Axonal Bouton Dynamics*. June 2017. ISBN 978-0-12803784-3. doi: 10.1016/B978-0-12-803784-3.00007-X. URL https://doi.org/10.1016/B978-0-12-803784-3.00007-X.

[3] Scivis contest 2023, 2023. URL https://sciviscontest2023.github.io/. Accessed: 2024-12-12.

[4] Li-Ru Zhao and Alison Willing. Enhancing endogenous capacity to repair a stroke-damaged brain: An evolving field for stroke research. *Progress in Neurobiology*, 163-164:5–26, 2018. doi: 10.1016/j.pneurobio.2018.01.004.

[5] Vida Demarin, Sandra Morović, and Raphael Béné. Neuroplasticity. *Periodicum Biologorum*, 116(2): 209–211, 2014.

[6] Marisa Brini, Tito Calì, Denis Ottolini, and Ernesto Carafoli. Neuronal calcium signaling: function and dysfunction. *Cellular and Molecular Life Sciences*, 71:2787–2814, 2014. doi: 10.1007/s00018-013-1550-7.

[7] Edith Kaan and Tamara Y. Swaab. The brain circuitry of syntactic comprehension. *Trends in Cognitive Sciences*, 6(8):350–356, 2002. ISSN 1364-6613.

[8] Robert Belleman. Scientific visualization and virtual reality: (bio)medical visualization and virtual reality applications. *Lecture slides, Visualization Lab & Computational Science Lab, Universiteit van Amsterdam*, n.d. Available from R.G.Belleman@uva.nl.