

UNIVERSITY OF TARTU
Institute of Computer Science
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Fedor Stomakhin

Web-based Toolbox for Interactive 3D Visualization of Neural Recordings

Bachelor's Thesis (9 ECTS)

Supervisor: Ilya Kuzovkin, PhD
Co-supervisor: Raul Vicente Zafra, PhD

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Web-based Toolbox for Interactive 3D Visualization of Neural Recordings

Abstract:

The visualization of brain activity is an approach that aids neuroscience researchers and medical professionals to explore the data they work with. In particular, 3D visualization of brain activity is a technique used when the spatial positions of data points in the brain are important. Numerous tools have been developed for the analysis and editing of various forms of brain activity. In this thesis, a web-based toolbox for interactive 3D visualization of neural recordings was implemented. The use cases of the toolbox were demonstrated by adapting it to visualize intracortical LFP recordings from 100 human subjects.

Keywords:

Computer graphics, Neuroscience, Local Field Potential, iEEG recording, Visualization, JavaScript, React, WebGL, Three.js

CERCS:

P170: Computer science, numerical analysis, systems, control

B640: Neurology, neuropsychology, neurophysiology

Veebipõhine Tööriist Närvisalvestuste Interaktiivseks 3D Visualiseerimiseks

Lühikokkuvõte:

Ajutegevuse visualiseerimine on lähenemine, mis aitab neuroteadlastel ja meditsiinitöötajatel uurida andmeid, millega nemad töötavad. Ajutegevuse kolmemõõtmeline visualiseerimine on tehnika, mida rakendatakse siis, kui andmepunktide ruumilised asukohad aju suhtes on olulised. On arendatud välja arvukalt tööriistu ajutegevuse visualiseerimiseks ja selle andmete redigeerimiseks. Käesolevas töös implementeeritakse veebipõhine tööriist närvisalvestuste interaktiivseks 3D visualiseerimiseks. Tööriista kasutusjuhtumeid demonstreeritakse, sobitades see 100 inimsubjekti korteksisiseste kohaliku väljapotentsiaali salvestustega, ning visualiseerides neid.

Võtmesõnad:

Arvutigraafika, Neuroteadus, Kohalik Väljapotentsiaal, iEEG-salvestus, Visualiseerimine, JavaScript, React, WebGL, Three.js

CERCS:

P170: Arvutiteadus, arvutusmeetodid, süsteemid, juhtimine (automaatjuhtimisteooria)

B640: Neuroloogia, neuropsühholoogia, neurofüsioloogia

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1 Introduction

The visualization of brain information is a subject at the intersection of neuroscience and computer graphics. Visualization in general is a useful supplementary technique that helps to explore data, its relationships and real-world mappings. The visualization of human brain activity relies on the representation of its external, measurable effects, such as gamma waves, fluctuations in bloodflow or electrical impulses. Such visualization can have scientific utility by helping make sense of measured activity, aided by the spatial and temporal contexts provided by the visualization.

This thesis implements a robust, interactive 3D brain visualization toolbox that allows researchers to conveniently review recordings of various types of intracranial brain activity in a variety of visual settings. The toolbox is a browser-based Node¹ web app rendered with ReactJS² on the client side. Graphically, it utilizes the WebGL³ API via the Three.js⁴ graphical library. This toolbox is publicly available at <https://festom-brain-toolbox.web.app/>.

In the second section, we give an overview of the preliminaries necessary for understanding and implementing an intracranial brain recording visualization toolbox. In the third section, a more detailed discussion and overview of the toolbox and its functionality follows. In the fourth section, we discuss the visualization of neural information and the adaptation of the toolbox to the provided data. In the fifth section, we provide a detailed description of the implementation details. Finally, we discuss the results and possible future developments.

¹<https://nodejs.org/en/>

²<https://reactjs.org/>

³<https://get.webgl.org/>

⁴<https://threejs.org/>

2 Preliminaries

The visualization of human brain activity broadly requires 3 general steps: gathering neural responses from the brain, processing the data and visualizing it in a user interface. In the following section we give an overview of the capture and representation of neural signals, followed by an overview of the relevant 3D web-based visualization technologies.

2.1 Capture and Representation of Neural Signals

Human brain activity is mediated primarily by roughly 100 billion neurons, a type of cell mainly found in the brain. Neurons communicate by sending each other action potentials - electrical events generated in axons, which are elongated root-like output structures of neurons. This electrical activity can be observed either non-intrusively, on the surface of the brain or internally. In addition to directly observing electrical activity, information about it can also be inferred by observing hemodynamic changes, which occur in response to neural activity [BUDL04].

2.1.1 Electroencephalograms

An electroencephalogram (EEG) is a technology that records the electrical activity of the brain via electrodes usually non-invasively placed along the surface of the scalp. Given the size of the electrodes and their external position, the activity is recorded on a macroscopic scale, with each electrode corresponding to a large volume of the brain. The test can be used to diagnose conditions such as brain tumors [MP13], brain damage [WHO99] and seizures [Ole11].

EEG data generally does not encode precise anatomical locations of its electrodes. This complicates its 3D representation, as the electrodes cannot be in that case represented in their positions relative to the brain. See Figure 1 for an example of EEG data showing the onset of an epileptic event.

2.1.2 Single-unit Recordings and Multielectrode Arrays

When attempting to measure electrical brain activity from particular neurons or a particular area of the brain, an invasive approach is often preferable. Single-unit recording is one such approach, where fine-tipped microelectrodes are precisely inserted near the desired neuron. However, a technique called multi-unit recording utilizes bulkier electrodes with larger tips to record the activity of several cells. Finally, even bulkier electrodes can record the aggregate local electrical activity (local field potential) of a large set of nearby neurons [LP17].

Local Field Potential (LFP) refers to the summation of synaptic electrical activity in a certain volume of the brain. It is possible to observe LFP signals by intrusively placing

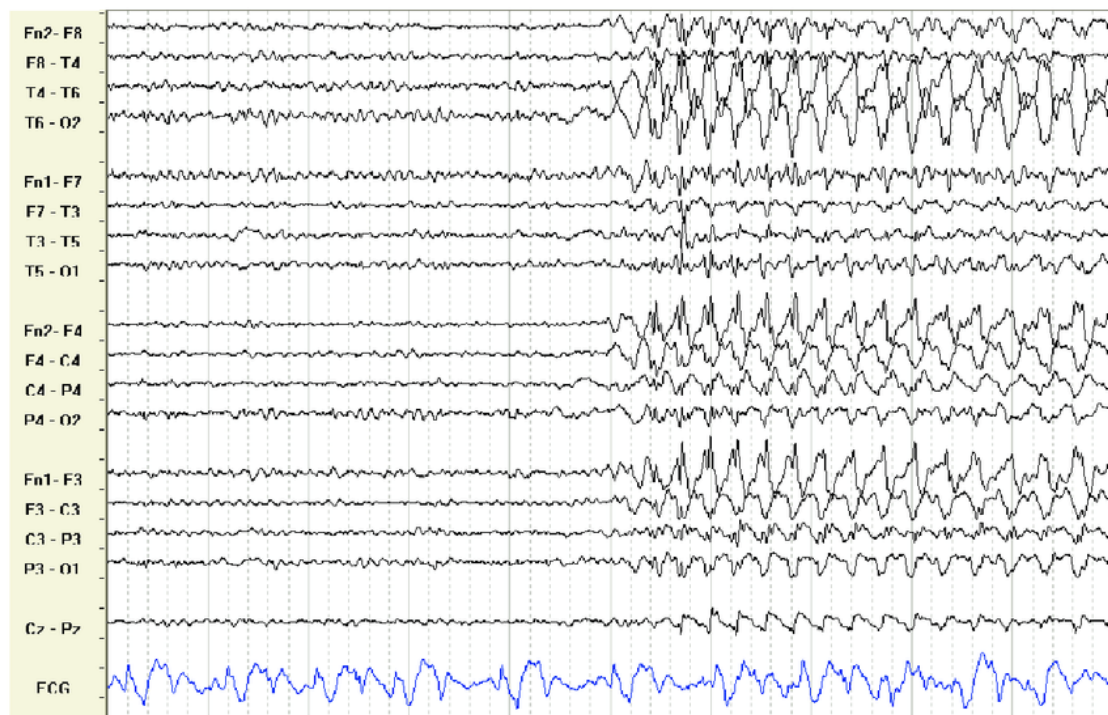


Figure 1. EEG data displaying the onset of an epileptic event [Ole11].

an electrode or a set of electrodes inside the brain. An LFP signal recorded by each such electrode is the average of the neurons' electrical activity in its proximity. While the crude nature and relatively large size of intracranial electrodes remains an issue for data resolution, it is nonetheless possible to extract valuable information about the workings of the human brain. The data gathered has implications for cognitive neuroscience [MF12].

Instantaneous correlations between neurons or brain volumes often provide more information about the activity of the brain than their electrical activity taken separately, as they contain information about the functional connectivity of the brain's different regions [Pes10]. For this reason, multiple sites within the brain or populations of neurons are often observed. A common invasive technique for this uses multielectrode arrays - wires or patches of electrodes implanted within the brain [ODB⁺15]. See Figure 2 for an example of LFP data gathered via an electrode array.

2.1.3 fMRI

fMRI, or functional Magnetic Resonance Imaging is a brain imaging technique measuring Blood Oxygen Level Dependent (BOLD) responses. Since neuronal activation requires oxygen and other nutrients, active regions in the brain receive a relatively greater amount

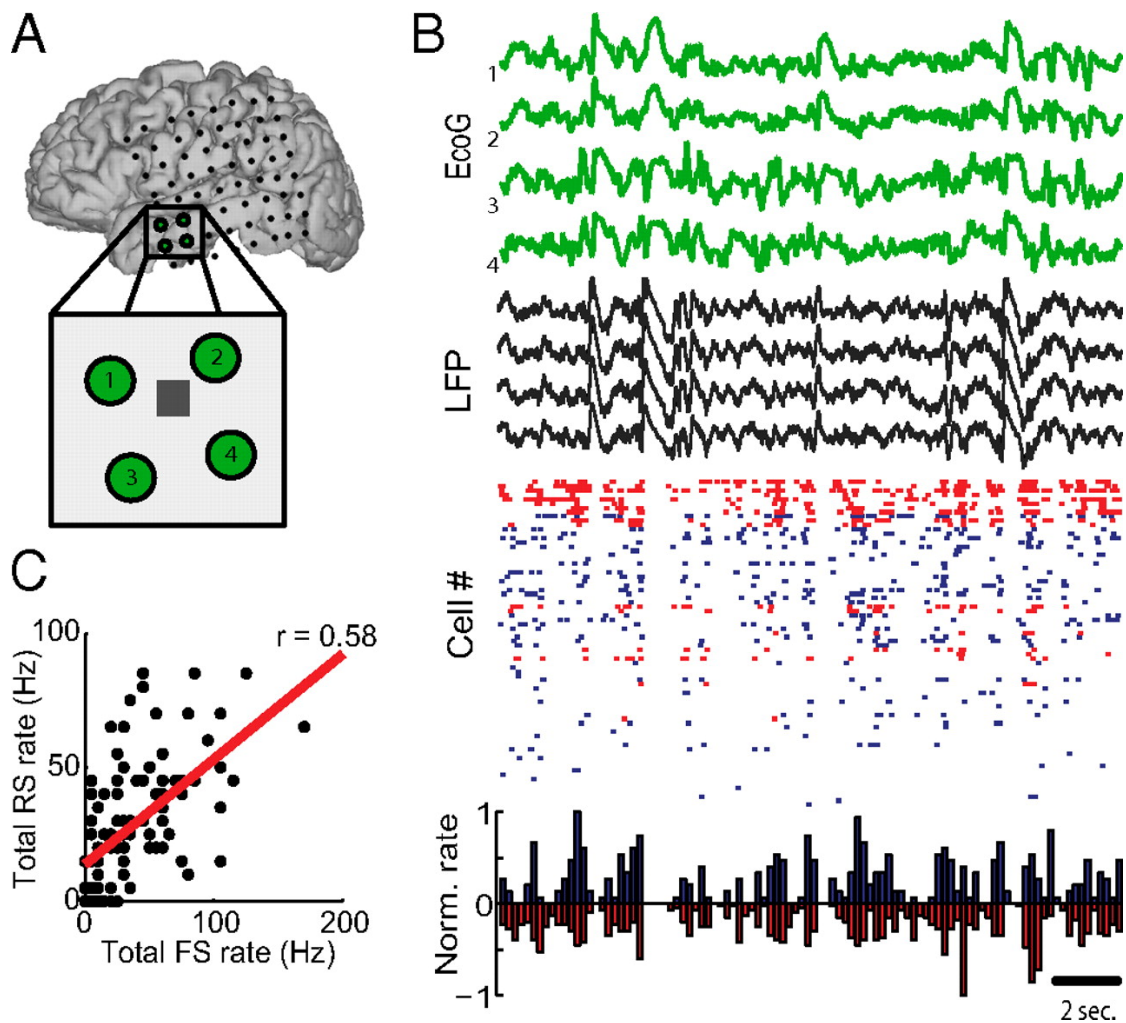


Figure 2. Sample intracranial EEG, LFP and unit recordings from [PDE⁺12]. (A) Localization of subdural electrodes. (B) LFP recorded from the NeuroPort is plotted in black.

of oxygen via the bloodstream, raising the blood oxygen level. fMRI can be used to observe hemodynamic changes in the brain thanks to the magnetic properties of hemoglobin, which gives oxygenated blood a different magnetic signature compared to de-oxygenated blood. The resulting data is spatially mapped onto voxels, with the standard size being $3 \times 3 \times 3\text{mm}^3$.

The size of these voxels and the frequency of BOLD response measurements correspond to the spatial and temporal resolutions of this technique. The limitations of fMRI are not related as much to its spatiotemporal resolutions, but rather to the structure of

the brain and the role that BOLD signals play. Higher fMRI resolutions require more elaborate BOLD-models due to primarily biological factors [GBL16]. It is not easily possible to separate the BOLD responses related to function-specific processing from those resulting from neuromodulation. It can also be difficult to extract meaningful BOLD responses from regions of the brain where functionally relevant neurons are sparsely populated, since other processes may cause the measured hemodynamic activity [Log08].

Functional MRI has a number of clinical and research use cases. Clinically, it is mainly used in brain tumour and epilepsy surgeries. Research-wise, it can be used to aid diagnostics of Alzheimer's disease, observe functional changes that result from traumatic brain injury and better understand psychiatric disease [OVG13]. More recently, it has also shown potential in the development of brain-computer interfaces [SLH⁺14].

Primary means of fMRI visualization are shown on Figure 3.

2.1.4 fNIRS

Functional near-infrared spectroscopy or fNIRS is a non-invasive optical brain imaging technique that measures hemoglobin (Hb) concentration changes in the brain by measuring the absorption of infrared light in brain tissue. Similarly to fMRI, fNIRS is an approach that relies on brain hemodynamics - differences in hemoglobin concentration are observed as a result of the bloodflow required to sustain brain activity. Unlike fMRI, it has a lower spatial resolution and cannot reach subcortical areas. See Figure 4 for a visualisation of fNIRS data. There is also a notable lack of widely-adopted fNIRS signal processing standards. [PSL18] [HWSM18]

fNIRS devices tend to be cheaper, more portable, tolerate more movement and have a higher temporal resolution than fMRI devices. This makes fNIRS particularly suitable for investigating brain function in developing brains, particularly in those of children and infants. Similarly, it is also suitable for imaging brain activity during motor tasks. [PTH⁺20]

2.2 Computer Graphics Preliminaries

The basis of 3D visualization is a canvas and a renderer. These are provided by a graphical framework and further elaborated in the "Implementation" section. For the purposes of this work, we used the Three.js graphical library.

Another important aspect of a 3D visualization is a projection, a method of displaying a three-dimensional object on a two-dimensional surface. Different projections are used when the general shape, size or some other visual characteristic of the data must be emphasized. Three.js implements a number of camera classes utilizing various

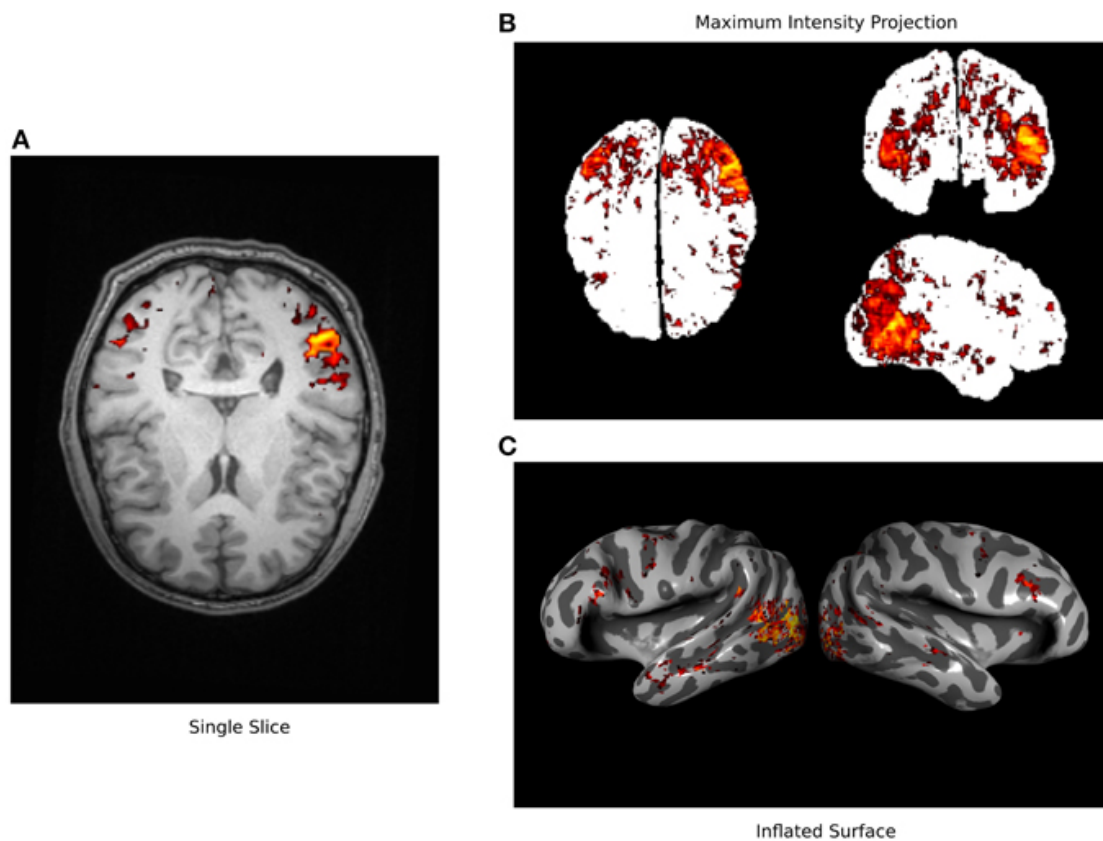


Figure 3. Three primary modes of fMRI data visualization from [GHLG15]. (A) Coloured data refers to voxels with values exceeding a statistical threshold. (B) Transparent brain, voxel values exceed a statistical threshold. (C) Inflated, non-transparent cortical surface, voxel values exceeding a statistical threshold.

projections⁵. The particular projection, together with the camera's position, rotation and other settings define a camera's viewing frustum.

The viewing frustum generated by an orthographic projection is a rectangular prism, making this type of projection particularly useful when it is important to preserve the relative sizes of the observed objects, while depth information and distance to the viewer is not as important. In various visualization applications, adjusting the near and far planes allows the viewer to selectively filter out objects that obscure the view. For example, given a very short distance between the near and far clipping planes, the frustum becomes a thin sheet, with only its contents visible.

The viewing frustum of a perspective projection is a truncated pyramid defined by a

⁵<https://threejs.org/docs/?q=camera#api/en/cameras/Camera>

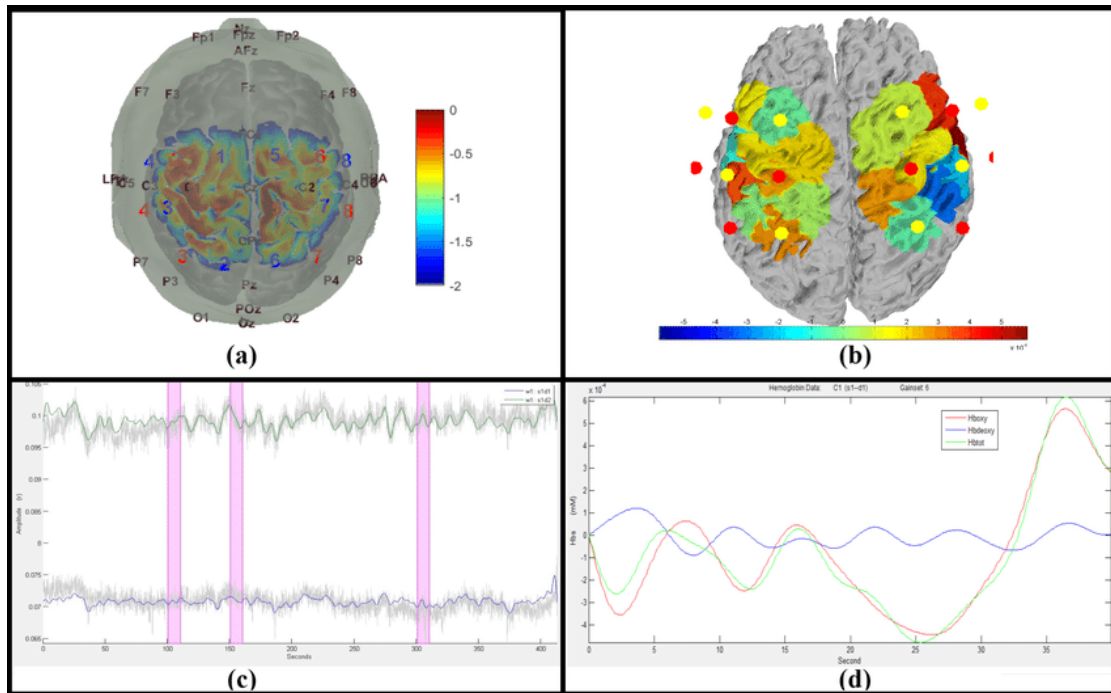


Figure 4. (a) and (b) visualize regional brain activation by employing various analysis software [AMAH20].

field-of-view value, corresponding to the angle between the pyramid's opposite lateral sides as they extend from camera origin at the apex. Perspective projection is a more natural type of projection, because it is similar to how a human eye focuses light into a focal point.

3 Brain Imaging Tools: an Overview

There is a number of brain visualization tools, which can interpret data resulting from various modes of brain imaging. Many of these tools are indexed on NITRC⁶ (NeuroImaging Tools & Resources Collaboratory), a web-based resource offering an overview of neuroimaging resources. For example, FreeSurfer⁷, an open-source neuroimaging visualization and analysis tool is oriented around the handling of MRI data. 3D slicer⁸, a free multi-purpose 3D data visualization toolkit supports the visualization of various forms of medical imaging data, and is compatible with FreeSurfer⁹.

Some tools are limited by their platform and usability, others by the type of data they take in. Our tool is easily accessible from the browser and takes in a set of .npy matrices as input. Similarly to FreeSurfer, it shows planar slices of the brain. Unlike it, however, our tool is oriented around the visualization of points, not areas. For this reason, it is particularly suited to the visualization of LFP signal activations. In addition, it is entirely browser-based.

⁶<https://www.nitrc.org/>

⁷<https://surfer.nmr.mgh.harvard.edu/>

⁸<https://www.slicer.org/>

⁹<https://discourse.slicer.org/t/new-extension-slicerfreesurfer/12751>

4 Interactive Visualization of Neural Data

In the visualization of LFP data, there is frequently no anatomical localization, and data is shown as a set of electrode activity line charts. In situations with a large electrode count, or when there could be large differences between the LFP activity recorded by various electrodes, an anatomical localization in 3D space could be used to observe these differences spatially. The toolbox implemented in this thesis aids in this pursuit. The toolbox is available at <https://festom-brain-toolbox.web.app/>. The web-based toolbox for interactive 3D visualization of intracranial brain recordings allows the user to visually explore user-provided neural recordings over time, navigate 3D space and sub-select user-selected stimulus categories, if given. In addition, the user can sub-select or omit various brain lobes to be rendered. See Figure 5 for the main interface of the web-based toolbox, showing 4 different views of the brain. Since the toolbox is a browser-based web application, no installation is required.

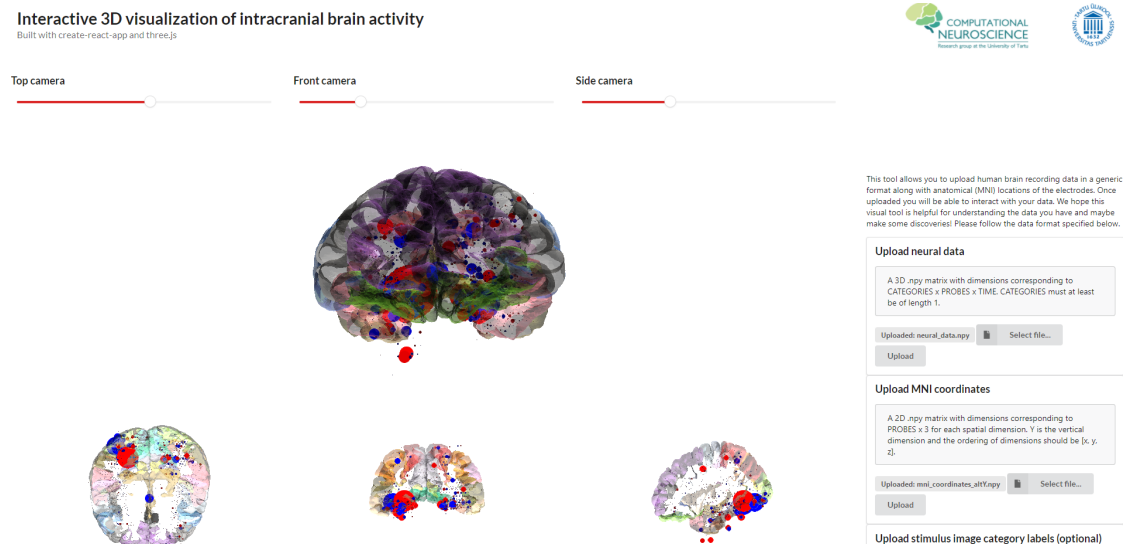


Figure 5. The main interface of the toolbox. On the left, the 3 planar views and a rotatable perspective view of the brain. On the right, the file upload dialogues.

4.1 User Interface

The toolbox is a single-page browser-based web application. Its user interface consists of a screen, a group of 3 sliders and a sidebar. The screen is subdivided into 4 viewports: one for each camera. The largest viewport shows the view of a perspective camera with

OrbitControls¹⁰. The three smaller ones underneath show a sheet of horizontal, coronal and sagittal planes. The position of the sheets can be adjusted with the slider group. The sidebar contains fields for uploading the three types of .npy files described above. It also contains a set of radiobuttons permitting to choose the stimulus category of the LFP data.

For additional interactivity, a dropdown was added, which permitted to sub-select the brain's lobes. To observe the change in LF potential over time, a time slider was implemented, allowing the playback of the user-specified recording. While the time dimension is discrete and consists of a set amount of moments, a recording is expected to be continuous. For this reason, the probe values were linearly interpolated between discrete moments. Finally, a planar view of the brain's "slices" was implemented.

4.1.1 Orthographic Projections as Planar Views of the Brain

A common approach to visualization of brain activity frequently used with MRI data is the so-called planar view. The brain is sliced into sheets, which are then viewed as 2-dimensional images, with the pixel values corresponding to the mean value of the sheet at the appropriate coordinate along its thickness. The author implements horizontal, coronal and sagittal views in a similar fashion, albeit with a notable difference. Since the data used can be considered sparse, as there is a limited number of intracranial probes, there is no volumetric view of brain activity to slice. Therefore, the brain mesh is simply sliced by use of an orthographic camera with the near and far planes corresponding to the sides of the resulting sheet (Figure 6), and the probe LFP activity is displayed as is.

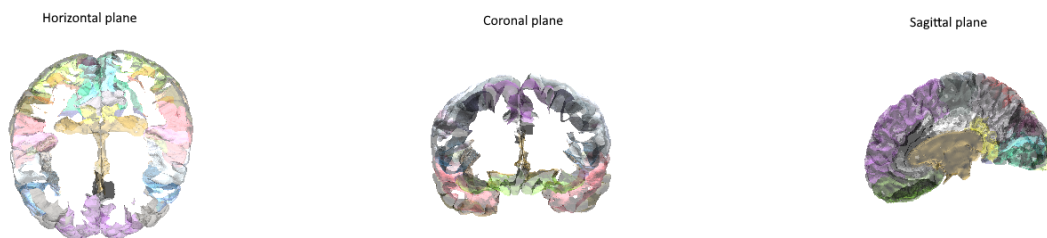


Figure 6. Three brain planes in the app. No activity data is uploaded.

¹⁰<https://threejs.org/docs/#examples/en/controls/OrbitControls>

4.2 Implementation

Several matters pertain to the implementation of the toolbox: requirements, issues and approaches. Requirements define the general direction of the implementation, while issues and approaches set its limits.

4.2.1 Requirements

The primary consideration in the requirements of the toolbox was the nature of the provided data. Brain recordings of LFP signals with intracranial probes are not full scans of the brain, and do not provide data on its structures. Rather, they contain information on the local field potential in the vicinity of the probe. In addition, the data is a recording, i.e. temporal, meaning that observing the changes in LFP activity over time, for example in response to varying categories of stimuli, is of interest. Finally, since the visualization was intended to be an interactive toolbox meant primarily for data exploration, a User Interface had to be designed. The UI would minimally require a canvas element for the main visualization, input fields for uploading .npy matrices and a way to traverse the temporal dimension of the LFP data.

4.2.2 Platform

In recent years, the advent of WebGL¹¹, a low-level JavaScript API, has permitted for increasingly complex graphical 3D applications in the browser [ERB⁺14]. It is based on the OpenGL ES 2.0 specification, which is a subset of the OpenGL API used in embedded systems¹². The WebGL API contains subtle differences in respect to OpenGL ES 2.0 due to the security and interoperability implications of its browser-based nature. WebGL is designed as a rendering context for the HTML Canvas element¹³. Given an HTMLCanvasElement, a WebGLRenderingContext is created, which manages the OpenGL state and renders to the simultaneously created drawing buffer.

Since the scope of the WebGL API is mostly limited to drawing points, lines and triangles¹⁴, libraries more accessible to 3D graphics developers have been created. One such library is Three.js¹⁵, which utilizes the WebGL API and handles the logic necessary for 3D graphics, with the scenegraph and the Renderer at its core. The Renderer¹⁶ utilizes the WebGLRenderingContext to draw the intersection of a 3D scene and a camera's frustrum to the HTML canvas element. The scenegraph¹⁷ is a hierarchical system

¹¹<https://www.khronos.org/webgl/>

¹²https://www.khronos.org/webgl/wiki/WebGL_and_OpenGL_Differences

¹³<https://www.khronos.org/registry/webgl/specs/latest/1.0/>

¹⁴<https://webglfundamentals.org/webgl/lessons/webgl-fundamentals.html>

¹⁵<https://threejs.org/>

¹⁶<https://threejs.org/docs/#api/en/renderers/WebGLRenderer>

¹⁷<https://threejsfundamentals.org/threejs/lessons/threejs-scenegraph.html>

of nodes, where the children's position and rotation matrices are relative to those of their parents. For additional convenience, Three.js also implements Meshes, Materials, Geometries, Textures and Lights.

For the purpose of creating a web application, the author opted for ReactJS¹⁸, a component-based open-source JavaScript library used for building user interfaces. It utilizes JSX, or JavaScript XML, which allows to build hierarchies of modular components with a syntax similar to HTML, to make UI implementation more convenient. On the initialization of the BrainScene React component, the brain model, renderer, scene and cameras are initialized. On upload of the probe coordinate and LFP matrices, they are loaded into memory and converted into JavaScript arrays. Category labeling is optional.

4.3 Representation of electrode activity

All probes are collectively shown as a single THREE.Points¹⁹ object. The size of each point scales proportionally to its corresponding probe value at the observed timestep. The neural activity values are linearly interpolated between timesteps in the vertex shader, for this purpose both the last and next timestep's information is fed into the shader. This permits for a smooth animation upon clicking the "play" button. To visually contextualize the data, the LFP signals were rendered as dots of varying size and color inside a semitransparent brain mesh. The colors are on a gradient from blue to red, with the positive values red and the negative ones blue. The sizes of the dots were implemented as a function of the absolute value of the LFP signal.

4.3.1 NumPy File Import Library Extension

There are numerous libraries which purport to transform .npy-format matrices to JavaScript arrays. These libraries seem to be built around the particular requirements of their users and are therefore not general-purpose. Since these libraries lacked the capacity to parse either half-precision float or fixed-length string or both dtypes, a "NumPy binary file parser for javascript"²⁰ library was extended.

4.3.2 Inactive LFP Dead Points

Nodes which had at a certain point in time low or minimal absolute levels of LFP activity were rendered as small black dots. This caused clutter and distracted from nodes which underwent bigger changes. To solve this issue, nodes with low neural activity values $v < 0.1$ were marked as ignored on the vertex shader and dropped in the fragment shader.

¹⁸<https://reactjs.org/>

¹⁹<https://threejs.org/docs/#api/en/objects/Points>

²⁰<https://gist.github.com/nvictus/88b3b5bfe587d32ac1ab519fd0009607>

5 Adaptation of the Toolbox to a Dataset of Human Intracortical iEEG recording

The author uses the data from a study by Kuzovkin et al., 2020 [KVPB⁺20], that studied perceptual categorization in the human brain. The data was originally gathered at the Lyon Neuroscience Research Center. It is a set of .npy arrays containing LFP signals recorded with corresponding deep intracranial probes. The probes were implanted inside 100 human test subjects' brains, as shown on the x-ray image in Figure 7.

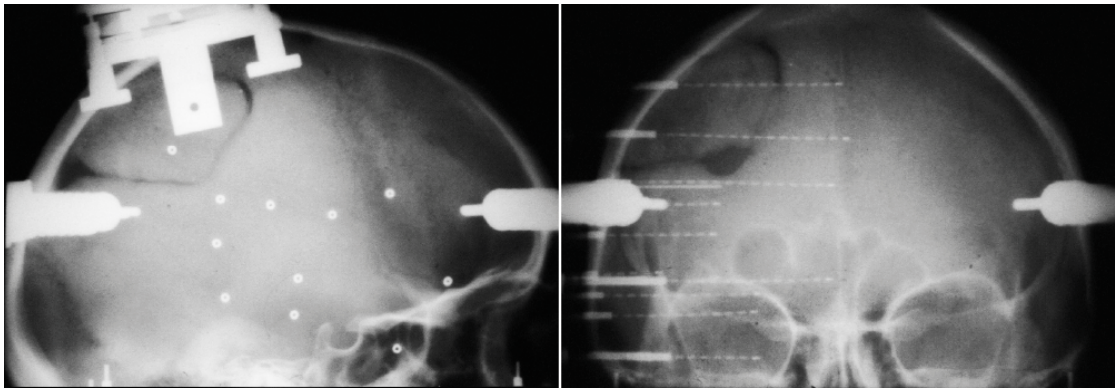


Figure 7. x-ray image of deep intracranial probes [KVPB⁺20].

The dataset allows to explore human brain activity during the task visual object recognition. The study [KVPB⁺20] analyzes the properties of neural signals during visual processing and highlights signal characteristics that are specific to certain visual image categories and distinguishes them from other categories as well as background brain activity. The dataset resulting of that was taken to demonstrate the functionality of the proposed toolbox. The toolbox allows to visually explore the findings of the aforementioned study and examine the results in an interactive manner, which could lead to insights about the signal propagation in the human brain during the task of visual object categorization.

5.1 Data format

The data from [KVPB⁺20] consists of several .npy matrices. The matrix `mni_coordinates.npy` describes the spatial locations of the intracranial probes. Its dimensionality is $(n \times 3)$, where n is the amount of probes. The matrix `neural_responses_ctg_lfp.npy` contains LFP data and has the dimensionality $(c \times n \times t)$, where c is the number of stimulus categories and t is the number of time-steps in which which the originally continuous

recordings were split. The matrix `categories.npy` has the dimensionality (c) and contains the labels of stimulus categories.

5.2 Visualizing Perceptual Categorization with the Toolbox

A version of the toolbox adapted to the data of this study was implemented as a University of Tartu Computer Graphics course project by Fedor Stomakhin, Hain Zuppur and Siim Parring. The result of this effort is a publicly available web page²¹ that allows the user to interact with the results of this particular study in an interactive manner.

²¹<https://brain-viz.web.app>

6 Conclusion and Discussion

In this thesis, a web-based toolbox for interactive 3D visualization of neural recordings was implemented. The toolbox is a React node application, utilizing the Three.js graphical library. The toolbox permits the visualization of brain activity, which was demonstrated on an recording of iEEG data. The toolbox can be useful for research and medical purposes, helping quickly visualize the neural activations of several types of recordings over time.

Numerous issues arose during the development process, related to 3D graphics, JavaScript libraries and the conceptual aspects of the application. In the course of solving them, the author gained an understanding of the challenges and the process of developing graphical web applications.

In the University of Tartu Computer Graphics course, taking place in 2020/2021 Autumn, a prior version²² of this toolbox was developed by Fedor Stomakhin, Hain Zuppur and Siim Parring, supervised by Ilya Kuzovkin as the course project. This team submitted the project to the University of Tartu DeltaX²³ competition, where it was awarded the II. place prize in the Digital solutions - Art in science category. Later, the project was extended to its present scope in the course of this thesis.

The toolbox has ample room for future development. For example, "unfolding" the 3D brain mesh into a 2D cortical map, and mapping the loaded nodes on the resulting texture could be of value. In the planar views, instead of rendering an orthographic section of the brain, a weighted voronoi mesh could be rendered, with the weights corresponding to node activations. The most valuable contributions would be, however, based on the requirements gathered from its audiences - researchers and medical practitioners. The gathering of these requirements should be the basis of future development of the toolbox. Finally, the robustness of the toolbox could be improved by refactoring its code in line with good JavaScript programming practices and migrating the project over to TypeScript.

The author extends his sincere gratitude to the supervisor Ilya Kuzovkin. For cooperation in the development of the Computer Graphics course project and the subsequent participation in the DeltaX competition, the author thanks course project team members Hain Zuppur and Siim Parring, and the Computer Graphics lecturer Raimond-Hendrik Tunnel.

²²<https://courses.cs.ut.ee/2020/cg/fall/Main/Project-BrainDataVisualization>

²³<https://delta.ut.ee/en/uncategorized/delta-x-2021-student-competition-final/>

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Appendix

I. Source Code

The source code for the web-based toolbox can be found in a GitHub repository with the following URL: <https://github.com/festom-brainviz-bsc-thesis/brain-visualization-utcg2020>. The source code in the state of the publication of this thesis is marked by the tag v1.0. The .npy input arrays can be found in the Data folder of the ZIP-file included with this thesis.

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