Virtual Reality for Understanding Multidimensional Spatiotemporal Phenomena in Neuroscience

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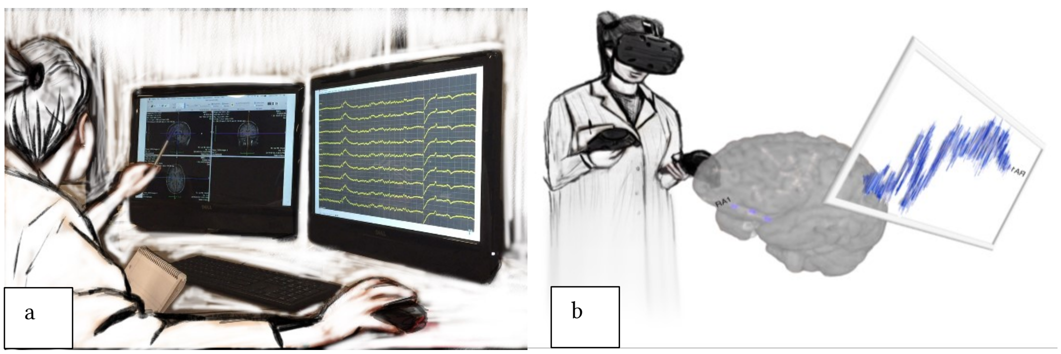

Figure 1: a) Traditional approach for the analysis of brain spatial and temporal datasets with two different tools. b) Our approach for understanding spatiotemporal phenomena in a brain with the situated context information.

ABSTRACT

Neuroscientists traditionally use information representations on 2D displays to analyze multivariate spatial and temporal datasets for an evaluation stage before neurosurgery. However, it is challenging to mentally integrate the information from these datasets. Our immersive tool aims to help neuroscientists to understand spatiotemporal phenomena inside a brain during the evaluation. We refined our tool through different phases by gathering feedback from the medical experts. Early feedback from neurologists suggests that using virtual reality for epilepsy presurgical evaluation can be useful in the future.

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CCS CONCEPTS

•**Human-centered computing** → **Virtual reality** • Human-centered computing → Scientific visualization • Human-centered computing → Information visualization

KEYWORDS

Multidimensional datasets; spatiotemporal datasets; immersive analytics; virtual reality; neuroscience; epilepsy presurgical evaluation

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1 Introduction

Patients with epilepsy sometimes have recurrent seizures that cannot be controlled by drugs, and treatment may include resecting a region where seizures happen and propagate. Before the surgery, neurologists conduct an epilepsy presurgical evaluation to precisely localize the seizure onset zone, which is done in part by using an electroencephalogram (EEG). In one evaluation approach, patients undergo an invasive procedure called intracranial EEG (iEEG) in which electrodes, called depth electrodes, are implanted directly in the patient's brain to record seizures and to determine the onset zone. Contact points record brain activities in electrodes. An MRI scan can help neurologists to locate the electrodes inside the brain.

They analyze 100+ time series EEGs in one system looking for seizure abnormal activities. Then, they reconstruct a 3D mental image of the brain by analyzing 2D MRI representations to localize the start and spread of seizures in the brain (Figure 1a). The high mental demand may result in tackling cognitive overload, reduction of performance, and increase in the chance for errors for neuro planning and neurosurgery [3].

We developed a tool that (a) integrates the medical data sets and (b) creates an immersive visualization in a physical space to aid neurologists in the task. Our tool, EPES (Epilepsy Pre-Evaluation Space), visualizes seizure propagation through the brain while the EEG panel is placed in the 3D space for showing required information (Figure 1b).

In this paper, we show how we iteratively improved our prototype by gathering feedback during a formative evaluation with two domain experts (co-authors of this paper). The improvement includes how EPES connects MRI and iEEG data by labeling, coloring and animation. Interacting and placing the required information i.e. iEEG recordings in the 3D space is also an enhancement of the system. The early feedback from neurologists suggests that using virtual reality (VR) for epilepsy presurgical evaluation is useful for connecting iEEG and MRI data as well as visualizing seizure propagation.

2 Related Work

Recently, some studies in the medical field focus on integrating and connecting iEEG and neuroimage brain scans. Brainstorm [2] is a non-clinical software tool for epilepsy presurgical evaluation. It shows where seizure happens. The colors of contact points change by the intensity value of activities. Each of iEEG recordings, MRI, and electrode positions can be imported and visualized in this software. The downside is, for each seizure event, a window (view) should be added for the analysis of the seizure propagation in a brain. GridView [10] proposes a 3D computer-based brain visualization with implanted electrodes for epilepsy presurgical evaluation. They use MRI images for the 3D brain visualization. The seizure zone in the brain is shown by color, but the seizure propagation is not visualized inside GridView. Also, the visualization of iEEG recordings is not included inside this software, and GridView communicates with another software to annotate when a seizure is happening.

Immersive environments have been used for the visualization and analysis of medical volume data. Sousa et al. [8] proposed bimanual touch interactions, in a stationary manner, easy to adopt for medical experts. While sitting, a user can analyze different image slices, scale, rotate, and change the brightness of 3D visualization of a medical image. Embodied Axes [5] includes a tangible interaction to address some problems of interactions in immersive environments with 3D volume which can result in fatigue in interaction and inability to detailed selection which required mid-air gestures. The 3D volume visualization is limited by three orthogonal tangible and actuated sliders. Also, the tool does not provide rotation interaction with data. FiberClay [6] visualizes 3D trajectories and interact with them. One of the applications of FiberClay is for showing neural pathways.

Immersive analytics have applications in the field of neuroscience and neurosurgical planning. Stadie et al. [9] showed that virtual reality software called Dextroscope decreased the preoperative guesswork and increased the surgeon's confidence during neurosurgical evaluation. Dextroscope, Dextrobeam, and Surgical theater are examples of virtual reality applications in neurosurgical planning. Some of their applications generate 3-D renderings from 2-D imaging data for planning tumor resection [7].

Up to our knowledge, EPES is the first tool visualizing seizure start and propagation for epilepsy presurgical evaluation in an immersive environment. Users can analyze data while moving or sitting as well as using interactions, such as rotating and scaling, with 3D objects using with mid-air gesture control. They can understand seizure propagation and analyze the required contextual information placed in the environment.

3 Approach

Typically, neurologists use 2D screens to visualize iEEG and MRI datasets that are used for presurgical epilepsy evaluation. The data is visualized side by side, but not integrated. As it is time consuming and challenging to mentally integrate these datasets, EPES addresses this problem in an immersive environment.

3.1 Integrating Medical Datasets

The recordings of iEEG can be 100+ dimensions, but data from each dimension is only relevant at certain points in time. Hence, based on time and space, our tool identifies these points and visualizes the information, highlighting critical times in each brain recording (channel). EPES shows a 3D visualization of the brain anatomy and implanted electrodes instead of 2D which helps medical domain experts to localize the seizure focus.

When a user selects a channel for visualization, the system fuses the recording and implanted electrode as the name of the channel and the corresponding electrode appears in iEEG graph and the brain hologram.

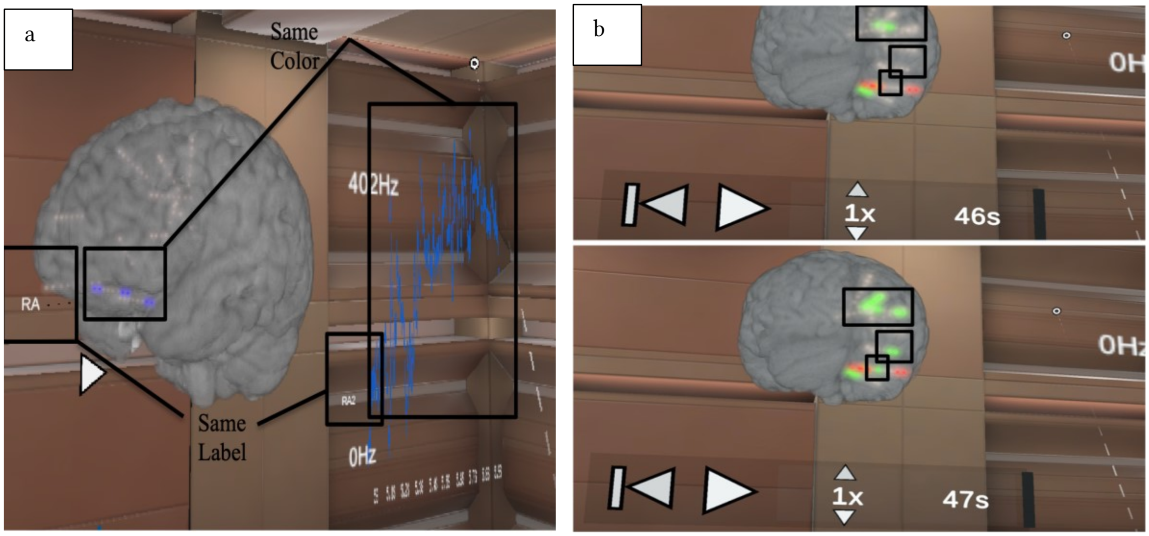

Figure 2: a) Colors and electrode names (labels) connect the brain hologram and seizure recordings, e.g., a color shows a seizure type, a subtle ictal rhythm, and a label shows the RA electrode name. b) The two images show how a seizure propagated through the brain within 1 second. For example, a seizure, with the annotated green color, is recorded in some channels at the 47th second.

We also use color coding to highlight seizure events in the multivariate iEEG data. By utilizing the same color encoding for highlighting electrode contact points in the brain when a seizure is happening, we create a connection between the iEEG data and the brain scan – making it easy for a neurologist to see how seizures propagate through the brain during a seizure (Figure 2a). Three colors, blue, green, and red, represent three seizure types: a subtle or questionable ictal rhythm, an established ictal rhythm, and recordings with the highest amplitude and frequency.

Figure 2b depicts the use of animation for showing the temporal dynamics of seizure propagation. The seizure propagation shows the connection between different areas of the brain where the seizure happens.

3.2 Using an Immersive Tool for Epilepsy Presurgical Evaluation

It is important to visualize both the brain and the recordings at the same time in the target medical case. One way is to use the available space of 2D displays but this limits the space allocated for visualizing the brain, recordings, or any other widgets, e.g., transparency or media control panels.

As integrating multidimensional visualization in 2D spaces can have physical limitations, using an immersive environment is one way to offer unlimited 3D spaces [4]. Our tool is designed to allow a user to navigate and control the display of complex datasets (100+ dimension in addition to 4D spatiotemporal seizures' propagation in a 3D brain) in space and time effectively and efficiently.

EPES aids neurologists to trace seizure propagation through the brain while spatially situating the iEEG graph in the 3D space based on their convenience. By using a head mounted display (HMD) with 6-degree-of-freedom (6DoF), which is HTC Vive, and two controllers, a user can interact, like rotating and scaling, with all objects in the immersive environment and understand seizure spread motionlessly or by physically moving around the brain.

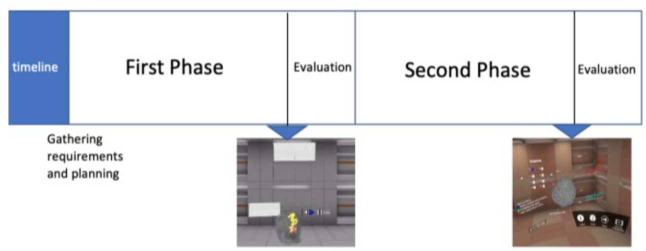

Figure 3: Formative evaluation setup

4 Formative Evaluation

4.1 Setup

The current version of EPES is based on two major development phases (Figure 3). The tool refinement is based on feedback gathered from two neurologists (co-authors of this paper) by the EPES research and develop (R&D) team (3-4 members). The first phase used a requirements' elicitation and resulted in the development of the EPES first version [1]. An evaluation session was held after each phase, and during the evaluation session, the R&D team asked the medical experts which design aspects meet the expectations and how to refine the design based on their expectations. The current version of EPES was also evaluated at the end of the second phase. During both phases we worked with the medical experts when any clarification was needed

4.2 Early Positive Feedback

The two neurologists provided early positive feedback about using the tool for epilepsy presurgical evaluation in the future. For the neurologists, it is exciting to work with an immersive technology for epilepsy surgery preplanning which is currently done using computer screens. They believe that being able to visually see the seizure propagation inside the brain and how different points in the brain connect through a seizure episode is beneficial. Overall, they expect that a deployed version of the tool will reduce their presurgical workload.

4.3 Iterative Refinement

We now summarize the tool's improvements after the first phase. Previously, direct lines connected the iEEG recordings and electrode visualizations. However, based on the feedback of neurologists, the increase in the number of links increases the cluttering. By using coloring and labeling for connecting iEEG and electrode visualizations, the iEEG panel is freely situated in the virtual environment. Using colors for showing different seizure types is another improvement of the software. Selecting channels for visualization is also a new feature. In the past, brains were visualized with the skull cover. However, the medical experts suggested a skull to be removed from the brain visualization, so the brain anatomy and where electrodes are placed can be clearly seen. Our tool now automatically removes the skull and shows only brain tissue. Comparing different iEEG recordings is important in epilepsy presurgical evaluation. Earlier, the tool visualized up to two iEEG recordings, but the increase in the number of recordings used to affect the performance. We improved the performance of the software, so a user can see the visualization of more than two iEEG signals without latency. Finally, a user can rotate, move and scale all the environment 3D objects. Earlier only moving a brain hologram was supported.

4.4 Future Tool Enhancements

Some room remains for feature improvements based on the evaluation after the second phase. The ability to slice a brain for cross section views and changing the visualization of iEEG line graphs based on some settings, such as controlling the iEEG channel sensitivity, should be added. Additional development can enable the tool to use other types of epilepsy monitoring, such as analysis with other types of EEG electrodes and using other neuroimaging like functional MRI.

4.5 Limitations

The evaluation had some limitations. For improving the software tool, we relied on the feedback of a limited number of participants, who are two neurologists and our team members. As all evaluators are part of the research team, a positive bias is likely present. We tried to reduce the risk of bias by making the critique sessions engaging and interactive, while probing for negative critiques. An increase in the number of arms-length participants will enhance the evaluation in the future and provide a more objective evaluation. Attracting a substantial number of neurologists to participate in a study will be an ongoing challenge.

5 Conclusion and Future Work

EPES visualizes iEEG data and makes seizure propagation easy to follow in epilepsy presurgical evaluation. The VR system externalizes the current process of mentally integrating various data sources to understand seizure propagation through the brain. We iteratively improved the tool based on design critique sessions with neurologists. Based on initial feedback from specialists, the immersive tool appears to be useful for epilepsy presurgical evaluation in the future.

We will evaluate our approach with more neurologists to have a better sense of the tool applicability and usefulness. It is interesting to compare different interaction techniques for the analysis of the mentioned problem. Our tool currently uses VR for deployment but using other immersive technologies such as augmented reality might be beneficial.

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