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Immersive 3D Visualization of Multi-Modal Brain Connectivity

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Abstract

In neuroscience, the investigation of connectivity between different brain regions suffers from the lack of adequate solutions for visualizing detected networks. One reason is the high number of dimensions that have to be combined within the same view: neuroscientists examine brain connectivity in its natural spatial context across the additional dimensions time and frequency. To combine all these dimensions without prior merging or filtering steps, we propose a visualization in virtual reality to realize multiple coordinated views of the networks in a virtual visual analysis lab. We implemented a prototype of the new idea. In a first qualitative user study we included experts in the field of computer science, psychology as well as neuroscience. Time series of electroencephalography recordings evoked by visual stimuli were used to provide a first proof of concept trial.The positive user feedback shows that our application successfully fills a gap in the visualization of high-dimensional brain networks.

1. Introduction

The field of experimental and clinical neuroscience constantly gains importance [YGL17]. In particular, the investigation of directed information transfer within the human brain is a growing field of research. While methods for the analysis of brain anatomy or brain-behavior relationships improve, large parts of the functionalities of the human brain are yet to be discovered. Understanding how the components of the complex neural network of the human brain interact and affect each other is essential to understand and treat psychological disorders or illnesses like Alzheimer's disease, epilepsy or forms of depression [BLM*16, LZP*10].

Interaction and inter-connectivity of neurons or brain regions is called brain connectivity and can be separated into three categories [FFK05]: *structural connectivity* refers to concrete neuroanatomical connections; *functional connectivity* describes the temporal correlations between neurophysiological events of spatially neighboring or remote neuronal structures and finally, *effective connectivity* is defined as the directed influence of one neuronal structure on another, mediated directly or indirectly. This connectivity can be derived from a variety of measuring modalities such as electroencephalography (EEG), magnetoencephalography, positron emission tomography and functional magnetic resonance imaging.

The resulting brain networks are of high dimensionality, providing information about directed information transfer depending on space (brain region), time and frequency. But how can such multidimensional data be effectively visualized? Current solutions either keep spatial context by showing reduced or aggregated data or have crowded abstract visualizations [BRK*17, FH16]. Aggregation leads to a loss of detail and the outcome depends on the parameters the data is aggregated upon. As abstract matrix-like visualizations can visualize time and frequency dimensions of the complex data, they lose the spatial context making it less intuitive and more difficult to understand. In this work we developed a novel visual analysis tool in an 3D immersive virtual reality (VR) environment. It shows the entire propagation over time for multi-frequency EEG-based brain connectivity while directly displaying the spatial information of the connected brain areas. This visualization in VR gives a more intuitive view of the data that provides the means for exploratory data analysis.

2. Related work

Visualization of brain connectivity. Currently, the analysis of brain connectivity [PKB*14] suffers from a dilemma: on the one hand it is necessary to consider all relevant dimensions – e.g. anatomical arrangement, temporal variance, frequency. On the other hand, drawing conclusions based on such complex views of the complete networks containing all dimensions is hard to achieve. A common solution to this problem is the reduction of illustrated dimensions. This can be achieved by means of restricting the view to a hypothesis-driven pre-selection of cortical region / time interval / frequency band, or a previous agglomeration of data [BRK*17]. Another well-established approach is to apply methods from graph theory in order to segregate the network into brain regions with similar topological properties [FH16]. However, in any case detailed information that has been recorded or derived gets lost.

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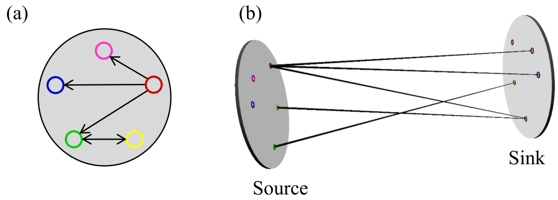

Figure 1: ***Illustration of a synthetic five-node network.*** *In subfigure (a), a directed network containing $D = 5$ nodes is shown; (b) provides the corresponding OD visualization.*

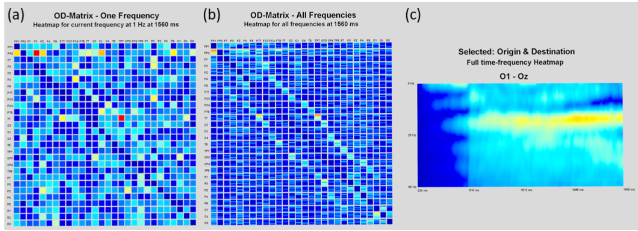

Figure 2: ***Extract of the adjacency matrix heatmap panel.*** *Subfigure (a) is restricted to one time point and one frequency; in (b) the time is fixed, the frequency varies. The time-frequency map in (c) shows the color-coded PDC values between the currently selected directed channel combination O1 $\rightarrow$ O2.*

Origin-destination flow visualization. The main goal of *spatially arranged* origin-destination (OD) flow maps is to show directed connections within a network corresponding to geographical locations [Har00,BBBL11]. A commonly adapted visualization approach is to duplicate the map into source and sink; that means one map represents the brain sources of information transfer and represents the brain destination of information transfer. A simulated example is shown in Fig. 1. In 1(a), the network is drawn in form of a node-link diagram. All connections (network edges) within the network are represented by directed arrows between the network nodes. In contrast, the OD representation in 1(b) shows the network in form of two reference spaces, separating the network into a set of sink nodes and one of source nodes.**Immersive Visualizations.** Immersive visualizations have been explored for many data types like 3D graph layouts [KMLM16, CHK*18, BVD19], multivariate data [CCD*17], or even multi-user applications on wall-displays [PLE*19]. Yang et al. presented a method for the visualization of OD data [YDJ*18]. In this work, the authors offer several representations of geographic flow maps and conclud that the 3D illustration should be preferred to the 2D alternative [YDJ*18].
These visualizations clearly show the advantage of using immersive environments for intuitive user interaction and spatial perception. The only immersive visualization directly designed for functional brain connectivity data is a web-based VR application, *NeuroCave*, proposed in [KZC*17]. Yet, the application does not illustrate *directed* network edges, and additional dimensions like time and frequency cannot be integrated. Therefore, we propose a new approach of immersive visualization of brain connectivity data by transferring well researched OD visualizations to an immersive 3D environment applying it to functional brain connectivity data.

3. Concept

Any visualization tool has to be realized with regard to the kind of data that have to be illustrated and essentially depends on the questions that have to be answered. The goal of the application presented here is to visualize high-dimensional brain networks derived from EEG data.

3.1. EEG-based brain connectivity

Raw Data. EEG data from an experiment investigating visual evoked potentials has been used [PLL*15]. We segmented this data into 40 repetitions lasting from 500 ms before and 1100 ms after the stimulus onset and were sampled down to 125 Hz in time; for the recording we used the classical 10/20 system for the arrangement of EEG electrodes (for details see [Pes16]).

Derived data (brain networks). This raw data is an example where multiple dimensions necessarily have to be included into network analysis [BTS*08]: connectivity may have a spatial focus and direction on the scalp; experimental stimulus requires for a time-variant network analysis; patterns have to be analyzed depending on frequency bands.
We apply the following strategy for the quantification of multi-dimensional brain connectivity data. First, data is approximated by the generalized multivariate Kalman Filter algorithm [MLA*10] which has proven to be an appropriate choice in the case of multi trial EEG data [GSVD15]. Based on the derived model coefficients, we quantify functional relationships within the networks by means of partial directed coherence (PDC), a multivariate, frequency-domain measure of directed information flow between multivariate time series [BS01]. The result per subject is a 4D PDC tensor with the modalities *node* $\times$ *node*-1 $\times$ *frequency bins* $\times$ *time steps* (in this case: $28 \times 27 \times 100 \times 201$). As an example, a conventional visualization such a tensor is shown in Fig. 2(b): every sub-block represents the color-coded, frequency-dependend, time variant connectivity between the nodes of the network.

3.2. Visualization of brain connectivity in VR

A heatmap panel as shown in Fig. 3 (lower row) is yet not sufficient to intuitively illustrate the complete 4D tensor. In particular, the spatial arrangement across the scalp is neglected. The combination of time, frequency and localization provides important information depending on the physiological paradigm that is analyzed. For that reason, we propose the simultaneous combination of different visualization techniques to jointly cover all modalities of the tensor: the conventional *heatmap panel* without spatial information; a *full time extended connectivity graph* (FTXC) that covers the whole time interval and preserves the anatomical arrangement; and the *time-selective connectivity* (TSC) illustration, providing a detailed spatially arranged view of the network at a certain time point. The view on all panels are synchronized for user interactions.

Heatmap panel. As depicted in Fig. 2, three additional representations complement the TSC and FTXC visualizations: one adja-

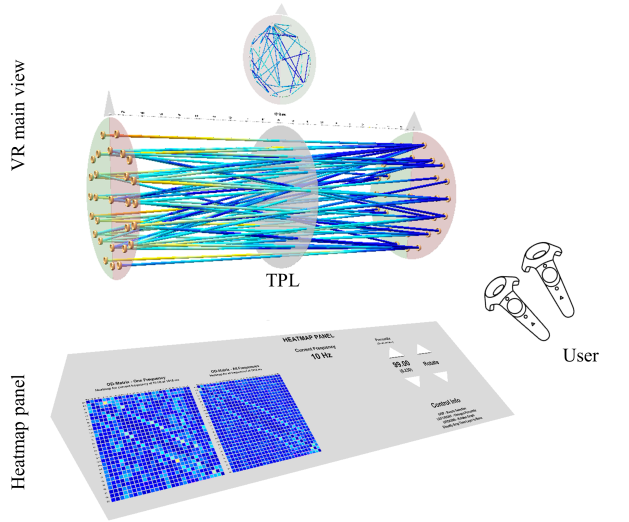

Figure 3: ***Virtual visual analysis lab.*** *This is the view provided to user in VR.*

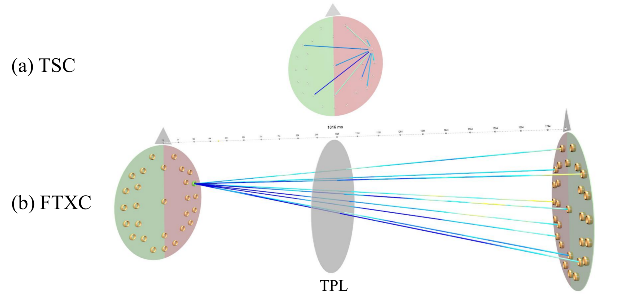

Figure 4: ***VR main view with selected EEG electrode.*** *In (a), the connections are displayed in form of a 2D head. It shows the network at the time point which is chosen by time pick layer in (b).*

cency matrix for the current time and frequency, one adjacency matrix comprising all frequencies for the complete time interval and one time-frequency map of a pre-defined directed channel combination. The purpose of this visualization is to get a first impression of the complete network which helps to exploratively find relevant time intervals or frequency bands that should be explored in the detailed views of 4(a) and (b).

VR main view: Full time extended connectivity graph. The FTXC (Fig. 4(b)) is the main graph of the visualization. It utilizes the enhanced 3D perception provided by VR environments by creating a novel visualization of the brain connectivity data across the whole time interval. Traditional visualizations of these networks focus on visualizing a fixed time point and therefore cannot represent the temporal evolution of brain connectivity. In this graph, source and sink of the OD data are separated as shown in Fig. 1. A simplified head is visualized as a disk with a triangle on top indicating the nose position, the hemispheres of the head are colored differently (green for left and red for right) to simplify interpretation of the graph from different viewing angles. Tubes connect the origin and destination electrodes for a selected frequency band. They are colored corresponding to their PDC value over time. Thus, the FTXC graph offers an insight into the *temporal evolution* of brain connectivity patterns.
Origin and destination electrodes can be selected to apply edge based filtering to the visualized graph. Furthermore, a time pick layer (TPL) between the origin and destination head allows the selection of a specific time step by mapping the space between the head disks to time.

VR main view: Time-selective connectivity. In Fig. 4(a), the TPL is transferred into a node link diagram with the PDC values that are mapped to edge colors. While FTXC shows the complete temporal evolution of the network, moving the TPL creates and animation of the temporal network evolution in the TSC. TSC and FTXC view have the purpose to supply the user with a means of an intuitive exploration and analysis of brain connectivity. This is mainly due to the anatomical arrangement of EEG electrodes as well as to the condensation of networks to the limitation of the view on certain time and frequency points. In addition to these visualizations, a 2D heatmap panel representation was designed, showing the complete network for all electrodes, time points and frequencies at once.

3.3. User Interaction

The interaction with the visualization is performed through direct interactions with the 3D scene by grabbing and pointing techniques and is accompanied by a 2D GUI that allows for fine-tuning of visualization settings. The user interaction is designed to motivate exploration of the brain connectivity data. The virtual scene shown in Fig. 3 is sized the way that the user is enabled to physically walk some steps to view it from different angles.

Grabbing and pointing. The TPL has to be selected by the user in order to move it to a specific time step. Since the user has to reach the time pick layer to grab it, it encourages to move into the 3D scene and to view the graph from different perspectives. Electrodes can be selected to apply a spatial filter based on the selected origin and destination electrodes. This is shown in Fig. 3(a) and 4: while in Fig. 3(a) all network edges are displayed, Fig. 4 exclusively shows the connection from the chosen source electrode (in this example electrode FT8). In contrast to the time pick layer, the electrodes are small. Furthermore the origin and destination electrodes are far away. Therefore, a pointing interaction with a ray from the controller is offered to the user in order to prevent fatigue by switching positions for selecting different origin and destination electrodes. In the heatmap panel it is possible to point to a certain directed channel combination within the adjacency matrix. A detailed time frequency view of the PDC values is then shown as a third heatmap. An example is given in Fig. 2, where (c) shows the connection from electrode O1 to Oz. All time points are included (x axis), as well as the whole frequency range (y axis).

2D GUI menu. In addition to the interaction in the VR scene, a 2D GUI is offered to the user. Here, one of the most important options is the choice of a frequency of interest which influences nearly all visualization of the network like the TSC and FTXC graphs.

Furthermore, it is possible to adjust a threshold or percentile of all PDC values for the connections that are drawn. The selected frequency is displayed in the heatmap panel and can be adjusted together with the percentile for filtering through a 2D GUI. In Fig. 3(b) for example, the frequency is set to 10 Hz and only connections higher than 90 % of all PDC values are illustrated.

4. Implementation

In this paragraph, we introduce the basic ideas of our proposed implementation. The prototype has been implemented in C++ and OpenGL.

Data management. During the import of data, a sorted 1D array of PDC values covering all frequencies and time steps is kept for the determination of the percentile threshold. This percentile is adjustable in the application, and therefore it needs to be accessed every time the percentile rank is changed. To quickly apply edge-based filtering in the rendering process, a 2D array is created during the import: it keeps the maximum value of every edge at each frequency and can be directly iterated to filter all edges with a maximum value less than the percentile threshold.

Graph rendering. The tubes representing the connections between origin and destination EEG electrodes are rendered as triangle strips. Dependent on the user's selection of threshold and electrode(s), only a subset of tubes is drawn but the information of the whole set of tubes is stored on the GPU.
The position of the time line is dynamically adjusted to not occlude the FTXC graph while being as readable as possible. For this the cylinder through the source and destination head disks is considered. Based on the tracked head position of the user the top silhouette line of the cylinder barrel is computed and the time line is aligned with this.
Point and select interaction with the VR controller is implemented via checking for ray bounding-box intersections between a ray coming out of the front of the controller and the bounding boxes of the EEG electrodes [Cha].

5. Evaluation

Evaluation strategy. In a first qualitative user study, the usability as well as the experience and effectiveness of the application have been evaluated. The VR application was tested with a HTC Vive Pro and two HTC Vive Controllers. A group of six participants was selected: three of them are PhD students in the research field of clinical neuro-psychology and work on EEG data. The other three participants are computer scientists; two of them work in the field of computer graphics, one is a front-end developer with experience in user interface design [Win19].
After a short introduction, the users had the task to explore the brain networks derived from the EEG data described in paragraph 3.1. For that purpose they had to solve a number of tasks and were instructed to consistently report what they want to achieve, what they are doing, what they had expected to happen and what actually happened (thinking-aloud method [BR00]). These tasks cover three aspects:

- *Interaction.* Example: "Move the TPL. Observe and describe the effects it has."
- *Spatial recognition.* Example: "Pick a point on an edge of your choice in the middle of the graph. Follow the edge to determine its origin and destination."
- *Heatmap panel.* Example: "Use the All-Frequencies OD Matrix and move through time to look for interesting connectivity values in other frequencies."

The full list of tasks can be found in the supplementary material S1. After the test phase, the participants were asked to fill a questionnaire where they could rate the overall experience. This questionnaire also includes the system usability scale (SUS) [BKM08]. For the SUS, participants have to give feedback to what extent they agree with ten different statements concerning the usability of the application on a five-level Likert scale, finally resulting in a score between 0 and 100. The questionnaire is provided in the supplementary material S2.

Results. Here, we describe an excerpt of basic evaluation results; the results of the complete questionnaire can be found in the supplementary material S3. In general, the new visualization concept received positive feedback. Five out of six participants agreed or strongly agreed with liking the overall experience, (item: "I think that I would like to use this system frequently."). Compared to the detailed view in the heatmap panel, the participants preferred the anatomically arranged visualizations of the networks (TSC, FTXC). Nevertheless they also found that the detailed view in the heatmap panel provides a beneficial complement. Transferred to the 0-100 score, the average SUS across the group yields 74.6. According to [Sau11], this value represents a good system usability considerably above average of other studies.

6. Discussion and Conclusion

In our user study, we included experts from the field of EEG data analysis as well as computer scientists. The results yield positive feedback for exploratory data analysis especially for the non hypothesis-driven use case. Participants liked the overall experience and experts with background in brain activity analysis could see themselves using this application in a professional context. This indicates that a 3D view of anatomically arranged brain offers a support for the user for a data-driven, intuitive exploration of temporally varying, multi-dimensional brain networks.
In our future work we will investigate whether the application may help for the visual analysis and comparison of brain networks between several subjects, groups or experimental tasks. Another open question is: to what extent does the VR view help to better understand network patterns in comparison to a 3D desktop view? Here, simulated time series with pre-defined network patterns (ground truth) are helpful to evaluate and quantify the benefit of the VR approach in a user study.

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