The Brain Matters: A 3D Real-Time Visualization to Examine Brain Source Activation Leveraging Neurofeedback

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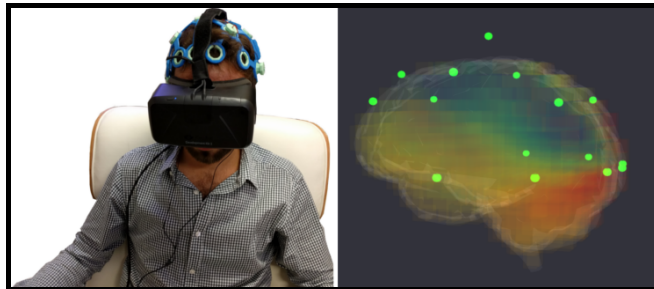{mariam.hassib}@ifi.lmu.de

Figure 1: Left: Participant during the pilot study with the BCI and VR headset. Right: Real-time 3D visualization of the brain source activation during the VR session.

Abstract

As Brain-Computer Interfaces become available to the consumer market, this provides more opportunities in analyzing brain activity in response to different external stimuli. Current output modalities often generate a lot data, such as an electroencephalogram which only displays electrode measurements. We introduce a three-dimensional real-time brain data visualization based on the measured values received by a brain-computer interface. Instead of visualizing the collected voltages by electrodes, we calculate a current density distribution to estimate the origin of electrical source which is responsible for perceived values at electrodes. Understanding where the centers of activation in the brain are allows to better understand the relationship between external stimuli and brain activity. This could be relevant in the context of information presentation for doctors to analyze pathological phenomena. A pilot study was conducted using Virtual Reality as input stimulus. Results indicate visible changes in real-time regarding brain activation.

Author Keywords

Brain Data Visualization; Virtual Reality; Neurofeedback; Electroencephalogram

ACM Classification Keywords

H.1.2 [Models and Principles]: User/Machine Systems — Human information processing
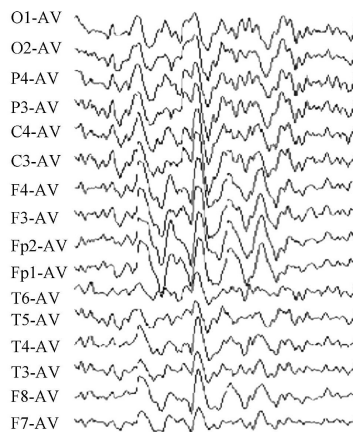
Figure 2: An EEG displaying a graph for each electrode. The output increases linearly with the number of electrodes.

Introduction

Brain-Computer Interfaces (BCIs) are a category of physiological sensors that are currently making their way into the consumer market. Traditionally, they have been used in the medical field to help patients with severe disabilities to gain more control over their lives. Electroencephalography (EEG) signals from the brain, gathered through electrodes placed on or inside the scalp, can be interpreted to allow patients to move a wheelchair, a cursor [11, 13] or provide feedback to the user in what is called a neurofeedback loop. Neurofeedback training involves interpreting brain signals in real time and providing the user with feedback about their state through different stimuli, for example, using Virtual Reality (VR) environments. Virtual Reality in combination with BCIs have been researched and used in several applications ranging from treating brain damage [10], substance abuse [6] to mindfulness training [1] (see Figure 1).

Using new, light-weight and less complex consumer BCI devices coupled with a VR system allows us to create adaptive virtual environments that can change according to the measured brain signals to increase or decrease activation in certain parts of the brain. This can especially help people with neuropsychiatric diseases (e.g. depression) and their doctors to investigate the brain activation in real-time during VR-based neurofeedback sessions. The desire to investigate the impact of VR scenes on the brain is high but becomes complicated because of linearly increasing output of an EEG over time (see Figure 2). Whereas the measured brain activity at certain electrodes is what drives the neurofeedback system, the origin of the electrical sources of activation inside the brain is also required to analyze which parts of the brain are affected by the VR scene. The low resolution electromagnetic tomography algorithm (LORETA) solves this problem for a sufficient number of electrodes in a three-dimensional space [9].

Our work presents a simple and understandable real-time visualization of the mentioned LORETA algorithm. A simulation is executed to show the correctness of the implementation. Furthermore, a pilot study is conducted to show that changes regarding brain activation can be observed in real-time.

Related Work

Research has already been done in the domain of investigating the impact of VR on the brain and brain data visualizations in general, which divides this section in two categories: (1) The impact of virtual reality on the brain in medical treatments and (2) currently existing brain data visualizations.

Baumgartner et al. has shown that neurophysiological changes can be found when using VR [3]. Increased brain activity at the parietal and frontal lobe could be found. The EEG analysis of the displayed VR scene was carried out using LORETA. However, the output cannot be inspected in real time and the implementation is not interactive. Grealy et al. performed a 4-week intervention program for treating patients with traumatic brain injuries using VR [4]. Significant cognitive increases could be noticed in terms of speech, visual learning and reaction times. Improvements were quantitatively measurable, but the affected brain parts by this training could not be observed at all. Hoffman used functional magnetic resonance imaging (fMRI) to investigate perceived pain when treating burn damages in combination with and without VR [5]. The fMRI has shown that distraction delivered by VR helps to reduce the amount of brain activity in pain-related brain areas. The brain scans presented in the study still lack of real-time capabilities to investigate the augmentation and impact of brain activation throughout a VR session. A three-dimensional visualization is presented by the project Glass Brain from the company
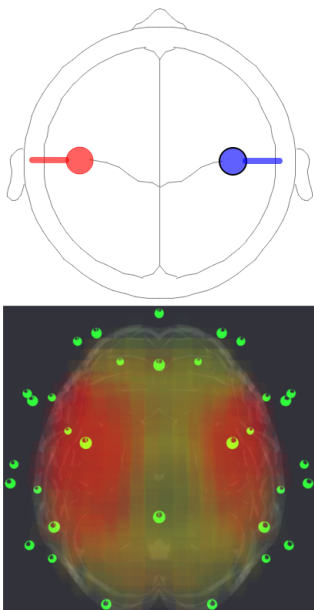
Figure 3: Evaluated sLORETA implementation. Top: Placement of two electrical sources in every brain hemisphere. Bottom: Recognition of both electrical sources by the sLORETA implementation. Green dots represent electrodes.

Neuroscape Lab[1]. It enables the visualization of source localization in real-time with interactive features. However, the inner of the visualized brain is hard to investigate since it is filled with a fixed solid color.

Overall, the presented brain visualization solutions lack of interactive features, real-time capabilities or suffer performance issues. In contrast our work shows a simple visual representation of the activities in the brain which allow human observer to understand the current brain activation in real-time. Currently we investigate this in two context: (1) Providing information to improve medical treatment of brain related issues, (2) assessment of reactions to visual stimuli in the context of human-computer interaction. In our work we propose a real-time implementation of LORETA including a three-dimensional representation enriched with interactive features to allow more precise investigations of brain parts. As a proof of concept, we performed a pilot study with an adaptive VR scene which changes according to the measured brain activities to achieve a neurofeedback session. Changes in brain activation are investigated during VR sessions in real-time as well as in post-hoc analysis.

System

The implementation of our algorithm uses neuromore Studio[2] as base platform. Together it builds a system allowing us to retrieve data measured by a BCI device and processing it with our implementation in real-time. Furthermore, we are able to create adaptive VR-based neurofeedback sessions based on the measured EEG data.

Localizing Electrical Source
We use a multithreaded implementation of the standardized LORETA (sLORETA) algorithm for electrical source local-

ization [8]. sLORETA allows precise source localization in a three-dimensional space with different settings regarding noise minimization, voxel density and the usage of a head model. The input of the algorithm are current voltages of extracranial scalp measurements received by the attached electrodes. sLORETA then calculates a density distribution throughout a head and associates each voxel with a magnitude which describes the current density power at the voxel. Voxels are color-coded depending on the calculated magnitude ranging from blue (weak) over green (medium) to red (strong).

Visualizing Results
After retrieving electrode measurements, the algorithm begins processing the data based on the chosen head model and number of voxels. We have decided to use a spherical head model because it is easier to reproduce and compare results from other research projects. The number of voxels can be set during program runtime, while a higher number of voxels increases the precision of the result at the cost of performance. Interactive features like zoom and rotation are supported to ease the analysis of brain source activation. The computation of the visualization algorithm is GPU accelerated. In contrast to current systems we are able to visualize the activated areas in real-time for the observer (doctor, researcher) to directly see the reaction inside the brain.

Evaluation
The implementation is evaluated using the BESA simulator tool[3] to verify the correctness of the results. The BESA simulator provides the functionality to place electrical source inside a head. These can be exported as csv file, which allows an import into the sLORETA implementation. The

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[1] www.neuroscapelab.com (last access 02-09-2016)
[2] www.neuromore.com (last access 02-09-2016)

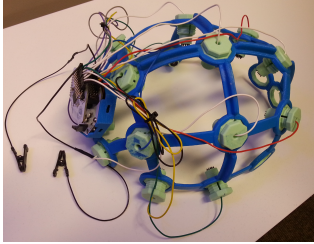[3] www.besa.de/downloads/besa-simulator (last access 02-09-2016)

evaluation showed that the algorithm is working correctly and can be used in future user studies (see Figure 3).

Input Stimulus
Our system uses VR as an input stimulus which enables us to create controllable simulations of real world situations where the reaction of body and mind can be analyzed. The simulation can be changed based on the measured electrode values to match a VR scene to the cognitive load of a user. Depending on the result of the EEG analysis, the difficulty of tasks or environments can be modified for brain training exercises, for example, to decrease frustration or boredom. Frequent training using VR with suitable parameters can be used to increase overall brain activity. Treatment of neuropsychiatric diseases often aim to increase brain activity in the frontal lobe, since decreased brain activity in these areas often are often seen in patients of depression, schizophrenia, substance abuse or obsessive-compulsive disorders [12].

Study

A pilot study with eight male participants was conducted to find visible changes of electrical source activation within the brain during a neurofeedback session that used VR to change the stimuli. The average age was 27.12 years ($SD = 5.19$). The participants were healthy and have not participated in a bio- or neurofeedback study before. The study took approximately 40 minutes per participant.

Apparatus
We used an OpenBCI[4] board with 16-channel support as EEG device for the study. OpenBCI and its electrodes are mounted on a 3D printed retainer which can be worn on the head (see Figure 4). An Oculus Rift[5] was used to display

Figure 4: OpenBCI mounted on a 3D printed retainer.
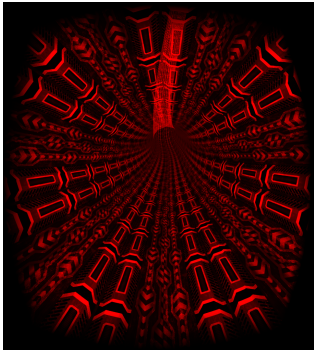
Figure 5: Tunnel traversed during the VR session.

VR content. The visualization uses 8000 voxels to render the results.

Method
The study is divided into a baseline task, a VR session and a repetition of the baseline task to see visible differences before and after the VR session. The OpenBCI is continuously recording EEG data to enable post-hoc analysis. Changes in brain activation are observed in real-time.

The baseline task is conducted to visualize initial source activation. The participant is asked to keep the eyes open for three minutes, followed by three minutes of keeping the eyes closed. Participants were seated in a dimmed room facing a white wall. This is a common task to estimate initial electrical brain source activation [2].

The VR session displays an infinite tunnel which is traversed by the participant for ten minutes (see Figure 5). The traversal speed is influenced by the activation measured by the sum of three electrodes at the frontal lobe. High alpha band magnitudes at these electrodes cause an increasing traversal speed while low voltages slowdown the traversal speed. We told the participant to traverse the tunnel as fast as possible. This training aims to increase brain activation in the frontal lobe. To achieve this, a signal processing algorithm is constructed which focuses on frontal lobe training (see Figure 7). The electrodes at the positions F3, F4 and Fz are used to estimate brain activation at the frontal lobe. The measured electrode values are summed up and processed in a fast Fourier transformation (FFT) to estimate frequencies in the range between 8 Hertz and 13 Hertz. The estimated frequency is normalized to the interval $[0; 1]$. The normalized values are used to set the traversal speed of the VR tunnel, where 0 causes the slowest traversal speed and 1 the fastest traversal speed.
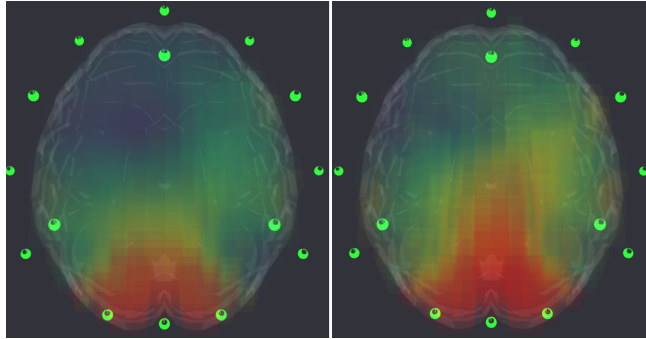
Figure 6: Brain source localization of participant 1 during the baseline task. Left: Brain activation during the eyes-opened task can be observed. Right: Brain activation during the eyes-closed task, which shows higher brain activation.
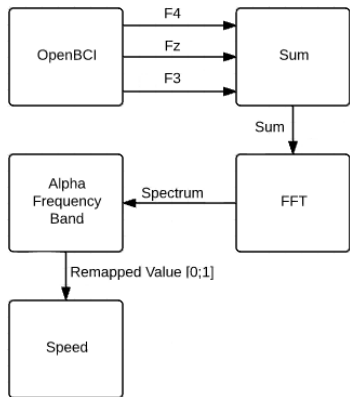

Figure 8: Brain source localization of participant 1 before and after conducting the VR session. Left: Localized brain activation before the session. Right: Localized brain activation after the VR session.

Figure 7: Flow chart of tunnel speed estimation during the VR session.

In the last step, the baseline task is repeated again. This is required to detect differences in brain activation before and after the VR session.

Preliminary Results
Results have shown that significant electrical brain source changes could be found within all participants. Figure 6 shows brain activation of one participant during the eyes-opened and eyes-closed task. Higher brain activation is noticed during the eyes-closed task. The most active part is the back of the brain which is responsible for visual processing.

Before and after conducting the VR session, a snapshot of brain activation is taken for comparison purposes. Figure 8 shows clear differences regarding brain activation before and after conducting the VR session. The brain shows higher brain activation before the session than the baseline task, which could be the effect of excitement since the participants have not participated in a VR related neuro-
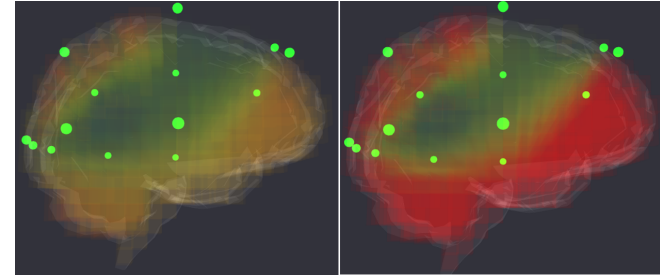
feedback session before. After conducting the VR session, higher brain activation was measured. Repetition of the baseline task shows higher brain activation than in the first baseline run (see Figure 9).

Discussion
Investigating brain source localization has shown that changes are visible and measurable when using VR as stimulus. Increased brain activity is observed when participants started closing their eyes. Previous research has shown that this is a natural effect [7]. The back of the brain is permanently active since it is responsible for visual processing. Closing the eyes pushes activity in other brain regions responsible for imagination and multi-sensory actions which explains enhanced electrical source localization during the eyes-closed task.

Considering the effect of VR as stimulus has shown increased brain activity in different brain regions. The cerebellum and the frontal lobe have shown improvement in brain activation. These regions are responsible for motion
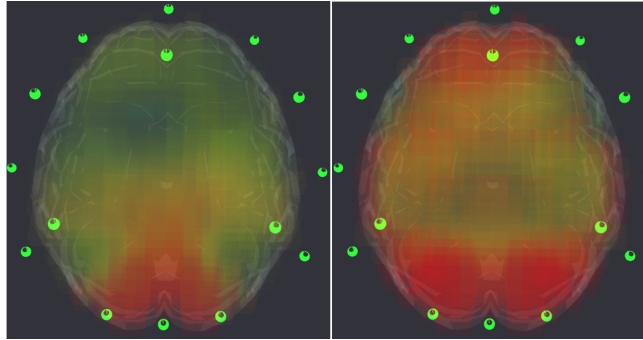
Figure 9: Baseline task repetition of participant 1 after the VR session. Left: Brain activation of the eyes-opened task. Right: Brain activation during the eyes-closed task.

sensing and motivation-related thinking. The changes in motion and speed in the tunnel explain brain activation differences in the cerebellum, while excitement and the desire to speed up the tunnel could explain enhanced activations in the frontal lobe.

The repetition of the baseline task has shown sustainable brain activity after the VR session. This is usually not a prolonged effect since permanent brain activation changes requires extensive neurofeedback training. Neurofeedback sessions have to be repeated several times for long term lasting effects.

The study has shown that real-time brain source localization can be used to understand the effect of stimuli on a neuropsychological level. Improved therapy of neuropsychiatric diseases and tailored enhancements of neurofeedback sessions are possible to increase treatment efficiency.

Conclusion and Future Work

We present an interactive three-dimensional real-time implementation of the sLORETA algorithm which calculates a density distribution to estimate the electrical origin of brain source activation. The usage of VR in medical areas has been investigated to estimate neuronal impacts on the brain using EEG devices. Our implementation of sLORETA is used in a user study to find out if it is possible to see visible changes in brain activation during a VR session. The results show that changes in real-time can be observed when using VR scenes as input stimulus. The outcomes can be used to optimize medical treatment methods or to identify neuropsychiatric diseases.

Our visualization proves visible changes regarding brain activation for different stimuli. Using this as first step, we want to find out if our visualization can be used to treat and identify neuropsychiatric diseases. Related research shows that neurofeedback can be used for treatment of brain related diseases like, Alzheimer, epilepsy or attention deficit hyperactivity disorders (ADHD). The usage of our brain visualization as analysis tool by doctors can help to identify upcoming diseases or track progression of existing diseases. Additionally we want to find out if it is possible to modify existing brain activation patterns by using dynamically changing VR scenes to train the brain towards an optimal state. The dynamic scenes should be able to change based on the values received by sLORETA and should not depend by the current electrode measurements. This requires operationalization of the results received by sLORETA. A quantitative analysis of all participants will be possible after substantiating the values calculated by sLORETA.

Acknowledgments

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