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Towards an Ecologically Valid Symbiosis of BCI and Head-mounted VR Displays

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***Abstract*—We present and discuss a user-friendly wearable brain-computer interface (BCI) system with a head-mounted virtual reality display (HMD) for motor rehabilitation of post-stroke patients. The described design represents the first building block toward developing a low-power wearable and ecologically valid BCI-HMD system for collaborative neurorehabilitation of motor and cognitive impairments. We discuss the system's main hardware and software components and applied methods leading to extracting and classifying the task-relevant electroencephalographic (EEG) brain waves used to control the HMD virtual reality environment. Pilot results using the system are also described.**

***Index Terms*—brain-computer interface, electroencephalography, head-mounted display, virtual reality**

I. Introduction

Over the last two decades, we have witnessed a significant increase in scientific and technological interest in human-computer interactions based on the brain-computer interface (BCI) principle [1]. The direct connection between brain activity and the control of a computer or other device is fascinating in today's technologically advanced world. However, we must admit that, despite this long-term effort, we are still far from the broad applicability of BCI technology in everyday life. The problem is two-fold: insufficient knowledge about brain activity associated with BCIs and underdeveloped technology [2]. Another critical missing element is incorporating social interaction, a natural part of many human activities in real life. This is also missing in most BCI implementations.

The development of virtual reality (VR) or augmented reality technologies moved BCI forward by creating flexible environments where human-computer interactions can take place and be modified. Head-mounted VR displays (HMD) move standard 2D screen-based visualization into a virtual 3D world (e.g., [3] and references in). While this shift brings another level of flexibility and enables the creation of immersive virtual worlds, there is even a greater need to address incorporating social interactions, so users don't feel alone in such an environment. This seems to be a more severe problem if the users of such an environment have limited communication, motor, or other cognitive aspects, for example, often observed in patients after a stroke.

There is increasing evidence of the positive impact of post-stroke training either based on action observation (mirror-box therapy, [4]) or active motor imagery (MI) nested in the entertaining designs for the patients [5]. An essential element of such training is its attractiveness and interest to patients. Attractiveness and interest are closely related to patients' acceptability and usability of such training concepts in everyday life. This is where VR comes in handy with its great flexibility, which allows the creation of a rich training environment that can be easily adapted and changed according to the patient's needs. Delivered feedback in the MI tasks closes the loop, and even patients with physically impaired movements can control the environment, and this is the point where we come to the BCI platform. Additional stimulating modalities, for example, tactile or functional electrical stimulation (FES), can further enrich the concept.

Our longer-term goal is to build a user-friendly wearable low-power innovative BCI system with an ecologically valid VR environment where users can collaboratively interact via their person-specific avatar representations. Here, we present the first step in building such a BCI-HMD system. In this effort, we follow our previous research and developments with a BCI-controlled robotic splint for upper arm motor rehabilitation[1]. By replacing the robotic splint with a VR environment, we move from a physical to a virtual world. Transferring such a system to the home environment represents a difficult but natural next hurdle.

This paper presents the BCI-HMD system principles from the point of the design, technical and algorithmic implementations, and pilot experimental results.

[1]http://aiolos.um.savba.sk/~roman/rrLab/

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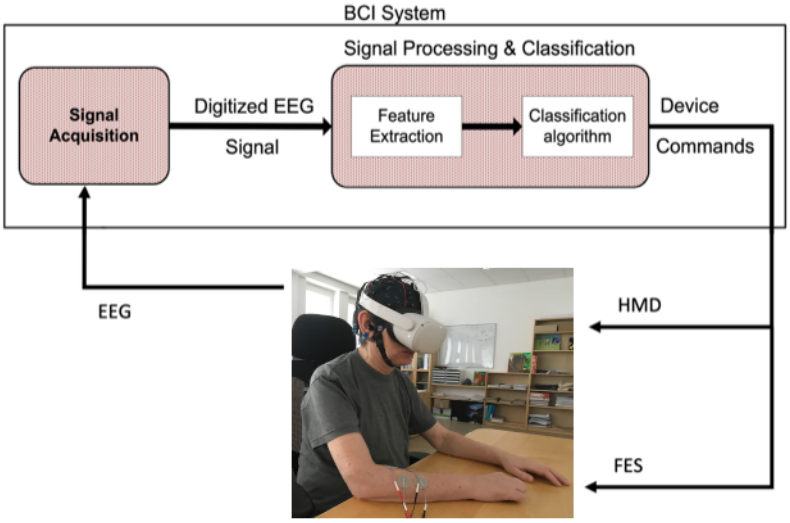


Fig. 1. The architecture of the brain-computer interface with a head-mounted display (BCI-HMD) and the functional electrical stimulation (FES) element. The core of the system is the BCI protocol implemented through the OpenVibe software. OpenVibe controls the EEG signal acquisition, processing, and classification and collaterally sends triggers managing VR animations in HMD and the start and stop times of FES.

II. BCI-HDM System Design

The BCI-HDM architecture depicted in Fig. 1 represents the standard BCI design consisting of

A. signal acquisition,
B. signal processing and classification and
C. environment control.

Publicly available OpenVibe[2] software for BCI and real time neuroscience is used to interconnect three major blocks of the BCI-HDM architecture. An autonomous Oculus Quest 2 (Meta Platforms, Inc.) headset with a fast processor, a new generation graphics card and 256 GB of internal storage is used as the HMD. The neurorehabilitation system is also enriched with an FES component applied to selected muscles. This is done through the programable two-channel externally controlled Microstim FES device (Medel GmbH).

A. Signal Acquisition

To continuously record EEG during the experiment, we use wearable (wireless) g.Nautilus PRO FLEXIBLE recording system (g.tec medical engineering, Schiedlberg, Austria). g.Nautilus PRO FLEXIBLE is a CE-certified and FDA-cleared wearable EEG headset to record brain activity in medical and clinical environments. In the most common setting, we use 12 active Ag/AgCl wet electrodes prefixed in an elastic fabric cap and two wet-clip electrodes. The electrodes are placed according to the international 10-20 system with six active left-side (FC3, C1, C3, C5, CP3, and O1) scalp electrodes, six active right-side (FC4, C2, C4, C6, CP4, and A2) scalp electrodes, one reference electrode (A1), and one ground electrode (AFz). A1 and A2 are wet-clipped electrodes placed on the left and right earlobe. Later, for signal processing, we use the signal from the A2 electrode to re-reference all EEG recordings to the average earlobe (A1-A2)/2 signal. The system can be easily adapted to record more EEG channels at different scalp locations. g.Nautilus PRO FLEXIBLE is a waterproof device with contactless charging, has 24-bit accuracy at 250 Hz or 500 Hz sampling rate, 2.4 GHz digital transmission up to 10 meters indoors, and allows 10 hours of continuous EEG recording.

EEG data are streamed in real time into the OpenVibe workspace using the built-in driver for g.Nautilus PRO. Raw EEG data are collected at the 250 Hz sampling frequency and resampled to 128 Hz in OpenVibe by calling the MATLAB (The MathWorks, Inc.) software routine *resample.m*.

B. Signal Processing and Classification

Resampled EEG signal is segmented into 2-sec long epochs, and a fast Fourier transform (FFT) with a Hamming window and the number of FFT points equal to 256 is applied. This is done by calling the MATLAB routine *fft.m*. This leads to estimating the amplitude spectrum from 0 to 64 Hz, with a step of 0.5 Hz. A product between amplitude spectrum values and spectral and frequency loading vectors of the parallel factor analysis (PARAFAC) model is computed [6]. PARAFAC belongs to a family of tensor decomposition methods and represents a powerful tool for detecting latent components in human EEG in the time-space-frequency domain. PARAFAC spectral and frequency loading vectors (signatures) are estimated offline using EEG data recorded during the mirror-box therapy or adapted from EEG data recorded at the previous training sessions. These signatures are not adjusted during the training sessions. A 2-sec window is moved with a predefined step which can vary, often 250 ms or 500 ms, and scores values computed across a predefined time interval are averaged and

[2]http://openvibe.inria.fr/

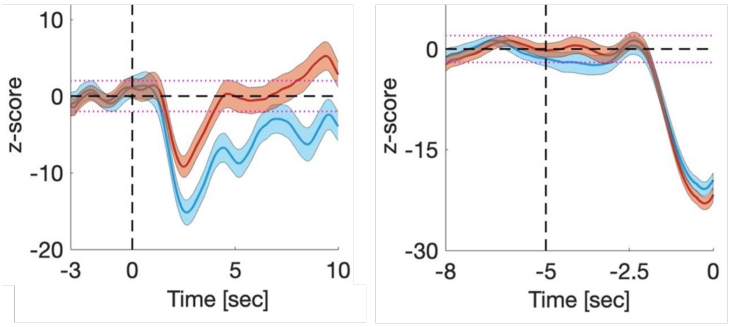


Fig. 2. An example of the PARAFAC time scores during the BCI training with the robotic splint. Z-scores of the PARAFAC time scores of the narrow-band oscillatory mu rhythm centered at 8 Hz are shown. See text for detailed figure description.

compared to a reference value. The average of the PARAFAC score values calculated during the resting period is used as the reference value. For example, score values computed across the 2-sec long intervals during the MI period are averaged and compared to the reference. This effectively means averaging eight score values if a moving step of 250 ms is applied. A comparison of the MI score values average and reference is solved through a threshold set in advance or adapted for every session or block of trials. Usually, the threshold is represented as a percentage decrease (event-related desynchronization, ERD) or increase (event-related synchronization, ERS) of the reference value.

PARAFAC is a generalization of PCA for dealing with multi-dimensional data. However, the uniqueness of the obtained decomposition gives the PARAFAC model an unsurpassed advantage over PCA [6]. Let's define a three-dimensional data array $\mathbf{X}$ $(I \times J \times K)$ of estimates at I time segments, J electrodes and K frequencies. Then, three loading matrices, $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{C}$ with elements $a_i^{(f)}$, $b_j^{(f)}$ and $c_k^{(f)}$ define the PARAFAC model which decomposes $\mathbf{X}$ and that can be mathematically described as

$$x_{ijk} = \sum_{f=1}^{F} a_i^{(f)} b_j^{(f)} c_k^{(f)} + \epsilon_{ijk}$$

where x_{ijk} are elements of $\mathbf{X}$, ϵ_{ijk} are the residual errors and F stands for a number of components (atoms) considered. In our setting, the columns of $\mathbf{A}$ represent time score vectors, the columns of $\mathbf{B}$ represent spatial signatures, and the columns of $\mathbf{C}$ represent frequency signatures of each of the F PARAFAC atoms. By restricting the PARAFAC model solution leading to non-negative spatial signatures and non-negative and unimodal frequency signatures, a set of PARAFAC atoms representing narrow-band oscillatory EEG rhythms can be obtained [7]. As outlined above, time scores of the oscillatory PARAFAC atoms can be used, either individually or as a combined set of atoms, to control the MI process with respect to the reference period.

Fig. 2 shows an example of this principle on data collected during the BCI training with the robotic splint [11]. In the figure, z-scores of the PARAFAC time scores of the narrow-band oscillatory mu rhythm centered at 8 Hz are depicted. The z-score values of the time scores are referenced to the last three seconds of the rest period and serve as a baseline, which precedes the MI period (Fig. 3). Blue curves represent z-scores of the PARAFAC model computed using five EEG electrodes placed over the left hemisphere, and the red curves using five EEG electrodes symmetrically placed over the right hemisphere. Solid line curves represent averages across trials, and shaded areas represent SEM (standard error of the mean). In the left plot, z-scores are depicted with respect to the 'move' command (0 sec; vertical dashed-line), starting the MI period. Both successful and unsuccessful trials are included. Z-scores of the three-second-long baseline period are depicted from -3 to 0 seconds. In the right plot, z-scores are depicted five seconds before the robotic splint movement (-5 sec; vertical dashed-line) and represent successful trials occurring more than 5 sec after the 'move' command. Z-scores of the three-second-long baseline period are depicted from -8 to -5 seconds. Note, in both plots, the placement of the three-second-long Z-score baseline on the x-axis doesn't follow the time continuity of the trial (Fig. 3).

PARAFAC atoms are extracted offline from EEG data recorded during the mirror-box therapy[3] carried out in 4 to 5 sessions before BCI-HMD experiments [11], [12]. In the pilot BCI-HMD studies, we focused on the subject-based extracted PARAFAC atom mimicking the mu EEG rhythm. The mu rhythm correlates with voluntary movement in the frequency range of 7.5-12 Hz. As part of a series of trainings, the initial PARAFAC model built on the mirror-box EEG data can be offline adapted using EEG data recorded during the previous BCI-HMD sessions.

C. Environment Control

OpenVibe ensures control of communication between individual parts of the BCI-HMD system. The EEG signal is transferred to OpenVibe in real time and is processed and evaluated as described above. OpenVibe implements a communication interface that sends information about starting the process of animations in the HMD VR environment. The

[3]Mirror therapy is an innovative treatment approach where an individual rehearses a specific limb movement by reflecting the movements of the non-paretic side in the mirror as if it were the affected side [8]. A link between motor imagery and passive action observation was found and associated with the concept of mirror neurons [9].

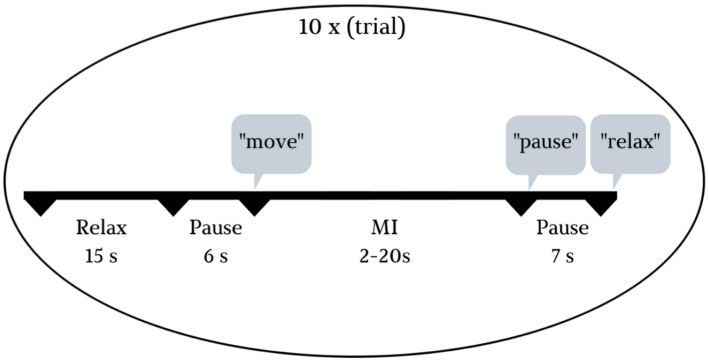


Fig. 3. The time scheme of a single trial motor imagery (MI) task. The trial consists of two conditions; the relax/resting and MI task periods. The audio commands 'relax', 'move', and 'pause' are played to instruct the subject to perform the given task.

commands from OpenVibe to the Oculus Quest 2 HMD are sent via a global Internet network.

OpenVibe also provides external control of the Microstim FES system. The commands to start and stop the electrical stimulation of muscles are sent via the USB interface. Their time is synchronized with the displayed movements in HMD, so the patient feels synchronized with the observed VR movements and muscle stimulation. Two pairs of adhesive electrodes are placed on the patient's forearm by a qualified physician to stimulate selected muscles. The type of impulses, duration, intensity, and total stimulation length are set before the training during a short manually controlled FES testing. The final setting of the FES parameters follows the patient's comfort and reactions to FES and is under the supervision of a physician. These parameters can be changed between the blocks of trials, for example, by increasing or decreasing stimulation intensity following the patient's reaction to stimulation.

III. Experimental Protocol

The time scheme of a single trial MI training protocol is depicted in Fig. 3. The trial starts with the audio command 'relax', after which the subject is asked to rest with eyes open or closed. He is instructed to rest without MI and limit other mind-related thoughts. After 21 seconds, the audio command 'move' is played, which triggers the period during which the subject performs the MI task. No specific instructions are given on the form of MI, but the VR schemes that the subject sees in HMD evoke the type of MI. Two events can occur during the MI task. First, the expected level of MI is reached, which triggers the collateral start of an animation in HMD and FES. This is counted as a successful trial. The new trial starts a few seconds after the animation in HMD and FES stimulation are finished by playing the audio command 'relax'. Second, suppose expected changes in the brain activity associated with MI are not detected. In that case, the trial ends after 20 seconds. The end of the MI periods is indicated by playing the audio command 'pause' or changing the VR scene. Afterward, the new trial starts again by playing the audio command 'relax'.

The timing of the individual trial periods can be modified according to the subject's feedback given to a therapist, the subject's performance, etc. The same is true for the number of trials per block and blocks per session/day. The pilot experimental studies generally tried three blocks consisting of 10 trials.

IV. Virtual Reality Implementation

For the current stage of the BCI-HMD system development, A-Frame and Networked-Aframe have been chosen as a software platform to implement the virtual environment. A-Frame[4] is a software framework for creating 3D virtual environments with HTML, CSS and JavaScript. The resulting environments are de-facto web pages and can run on any device with a modern web browser. In addition, A-Frame supports most of the contemporary virtual reality hardware, such as handheld controllers, stereoscopic displays, and VR headsets (HMD). Networked-Aframe[5] (NAF) is an add-on for A-Frame, allowing multiple users to share virtual environments in real time. NAF also supports audio chat, which is important for the voice commands of the BCI-HMD system. The primary reasons for choosing this software platform were the ease of deployment and hardware independence. And, as the experiments performed in [10] demonstrated, the platform gives a fluent user experience, provided that the virtual environment complexity is kept in check.

The virtual environment uses a client-server architecture with two types of clients (Fig. 4). Two different protocols are used for communication between the server and the clients. Via the http protocol, the assets the environments are composed of are provided in synchronous mode, and therapy configuration is handled in asynchronous mode. The server also uses the http protocol to receive commands from the signal processing and classification (SPC) component of the BCI-HMD system. The full duplex communication, provided by the WebSocket protocol, is necessary for real time updating of shared elements of the environments, including arm animations.

[4]https://aframe.io/
[5]https://github.com/networked-aframe

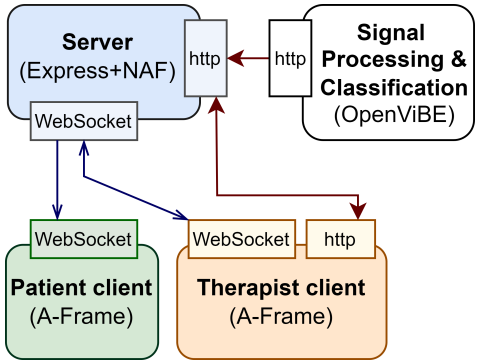


Fig. 4. Virtual environment architecture.

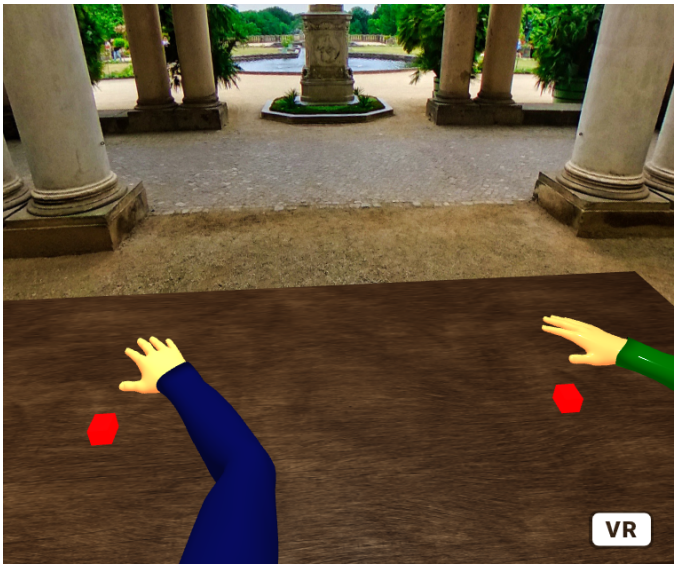
The user interface of the therapist-client is more affluent as it provides both a 3D virtual environment with corresponding animations and a panel to set up parameters and control of the therapy session (Fig. 5). An example of the 3D virtual environment depicted in Fig. 5a represents a scene with a table on which an arm and an object are placed. One pair of the arm and object belongs to the therapist (green arm) and one to the patient (blue arm). It is possible to perform specific animations with the arms and objects, such as moving or turning around the object. The therapist's animations of the green arm are performed from the control panel (Fig. 5b). A command can trigger the blue arm animation from the SPC component, which is evoked by the patient's MI strategy. The control panel also allows to set up of a therapy session. For example, the number of MI trials, the time when the environment waits for the SPC component's command, the virtual environment's background, etc. It is also possible to calibrate the blue arm position to induce a more substantial feeling that the VR hand belongs to the patient. The patient interface contains only the virtual environment in HMD, similar to the one in Fig. 5a.

V. Experimental Results

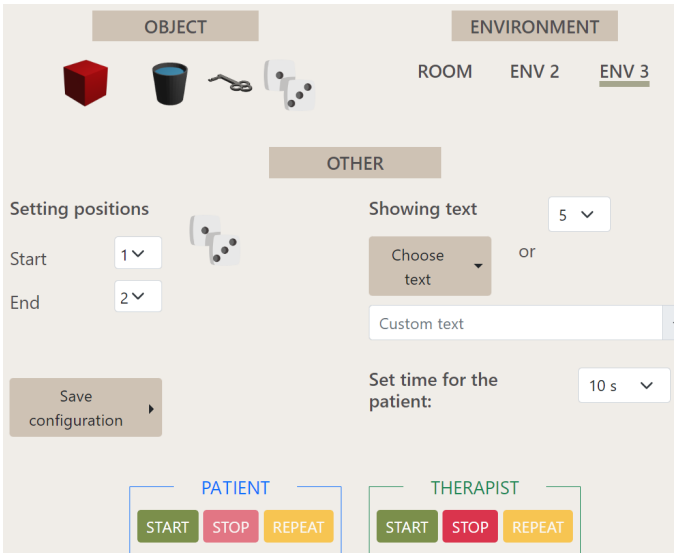
The BCI-HMD system was tested on a healthy 52-years-old man and a patient with right-hand hemiplegia due to an ischemic stroke. The patient is a 61-years-old man who participated in our previous neurorehabilitation therapies with the mirror-box and BCI robotic split [11], [12].

Sessions with the healthy volunteer focused on fine-tuning the software and hardware parts of the system. Clinical and electrophysiological EEG changes were not analyzed and evaluated. The subject reported an excellent acceptance of the system without discomfort or induced more significant mental fatigue.

A detailed training protocol with regular clinical testing was planned for a subject with hemiplegia. This plan was interrupted due to the covid pandemic. The training was restarted in mid-October 2022 and is scheduled for 5-6 weeks, with 2-3 sessions per week. At the time of writing, we can report on one pre-training session which was carried out. The PARAFAC model using data from the subject's previous BCI robotic splint experiments was applied to control the HDM VR



a)



b)

Fig. 5. Parts of the therapist-client environment: virtual 3D environment (a) and control panel (b).

environment. The FES stimulation was involved. The subject successfully used his MI strategy in a series of trials to control the VR visualization sequence. Online visual inspection of the mu rhythm PARAFAC time scores indicated the expected changes between the resting and MI periods. Following this experience with the BCI-HMD system, the subject showed strong enthusiasm for further participation.

VI. Discussion

We outlined the hardware and software design of the BCI-HMD system with FES for motor rehabilitation of subjects after stroke. Although the system was not thoroughly and clinically tested, it consists of sub-parts tested previously. The past knowledge and experience with the BCI-based robotic

splint speeded the development of the current VR-based system [11]. The transfer from the physical robotic movement to the VR environment, where the feedback is evoked through movement-related animations, is motivated by the expected higher flexibility leading to the creation of varieties of visual feedback. This fills an essential aspect of any neurorehabilitation training: the subject's joy and interest in participating in the program. Our intention goes even further. As part of the ReHaB project (EU CHIST-ERA grant), we are trying to include a therapist in VR and thus create a collaborative VR environment where the social aspect of rehabilitation is maintained. We expect even greater subject engagement and interest in this collaborative motor rehabilitation training form.

For this effort to be successful, it is also necessary, on the hardware side, to build a user-friendly wearable low-power BCI-HMD system. The system should be non-obtrusive, comfortable, and easy to operate for the subject. A miniature system for recording the EEG signal with sufficient quality and easily implementable EEG electrodes is an essential part of the HDM design. The same is true for the EEG processing and evaluation system, which must be low-energy and compact to be built into the wearable system. Together with the project partners, our research is moving in this direction.

Utilization of 3D virtual environments, projected stereoscopically via HMD, may significantly increase patient motivation and enthusiasm for neurorehabilitation. Therefore, one of our intentions is to bring a rich, almost first-person 3D game-like experience to the rehabilitation sessions. Concerning this, we also evaluate the usability of contemporary 3D game engines for creating the virtual environments of the BCI-HMD system.

Acknowledgment

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