A Study on EEG Power and Connectivity in a Virtual Reality Bimanual Rehabilitation Training System

D.A. Blanco-Mora, Y. Almeida, C. Vieira and S. Bermúdez i Badia

Abstract— **The study of neural processes that describe bimanual activity in areas such as neurology and rehabilitation are of high interest, in particular for rehabilitation after brain injury. However, brain processes during bimanual motor rehabilitation are not fully understood during stroke rehabilitation. Hence, it is not clear how to exploit them and their possible advantages in an EEG driven Virtual Reality (VR) training. In this work, VR and EEG were combined to study the neural processes in motor areas during bimanual activity in a serious game, involving two kind of movements: Left to Right (L2R) movement (Right handle forward and Left handle backward movements) and Right to Left (R2L) movement (Right handle backward and Left handle forward movements). 10 right handed healthy people (7 Males, 3 Females, 29.9 ± 6.21 years old) participated in this study. As it was expected, differences between rest and bimanual activity conditions (L2R and R2L) were found, surprisingly, on lowest frequency bands, Delta and Theta. More relevant results were found on Delta band at the right Hemisphere and inter-hemispherical relations, specifically for intra-hemispherical connectivity for CPSD relations with p=0.005 (L2R) and p=0.02 (R2L), and power quantified with PSD with p=0.023 (L2R) and p=0.03 (R2L), while inter-hemispherical connectivity got lower values on resting compared to L2R movement with a p=0.015. Besides, comparisons between resting and movement in Theta band showed significant results for inter-hemispherical connectivity (p=0.03, L2R vs Rest, and R2L vs Rest) and differences in power for Left Hemisphere (p=0.05). Finally, non-significant differences were found in motor cortex between the two kind of bimanual activities tested on this work. These results create an opening scenario to test for mirror effect of bimanual activities from one hemisphere to another on populations with hemi paretic conditions, aiming to apply it in a near future as therapy for Stroke Survivors.**

I. Introduction

Body movements comprise the activation of a part of the body and the coordination among its joints. These motor movements engage different brain areas from all the lobes for the targeted movement to be achieved, with specific brain activation patterns depending on the particular motor task [1]. Bimanual movements involve different brain areas from both hemispheres such as the premotor and primary motor cortices, and interactions between them. More concretely, the Inter-hemispheric Inhibition (IHI) [2] between both primary motor cortices (M1) through the corpus callosum. The later playing an important role in bimanual activities, as demonstrated via Transcranial Magnetic Brain Stimulation protocols [3].

Previous works studied engagement of motor cortex in rhesus monkeys [4] and movement prediction [5] from primary motor cortex cell activity. Those studies concluded that it is possible to decode the direction of movement for both unimanual and bimanual movements even when the two arms move simultaneously in different directions. However, the acquisition of brain cell activity was done using invasive techniques and surgery. On less invasive approaches, there have been multiple studies using fMRI to identify the activation of brain areas for specific movements, being tapping finger movements the most researched one [6]. The main reason for this is the constrained setup that limits and makes it difficult or even impossible to study most motor activities. However, these studies have shown that different areas play different roles in the movement, and that their interconnectivity is an important piece in bimanual activities.

A strong candidate that can describe neuronal activity from bimanual interactions without an invasive intervention or the constrains of fMRI is Electroencephalography (EEG). Besides, Brain-Computer Interfaces (BCI) based on EEG have been used for decades to translate neuronal rhythms to actions, improving the quality of life of handicapped people [7]. Nevertheless, because the complexity of describe bimanual activities, BCI applications have been mostly focused on studying unimanual activities [8]. For this reason it is not yet clear which EEG features are needed and how to translate neural signals to bimanual movements. In the particular case of stroke rehabilitation therapy, the most widely applied methodologies focus on unilateral limb recovery, leaving aside that bilateral and bimanual activities [9], and how those could improve neuroplasticity.[10].

To tackle the above limitations, In this work we associated upper limb post-stroke rehabilitation training with bimanual motor activity through the development of a bimanual gamified VR task and simultaneous EEG recordings. The aim of this work was to study and explore Intra and Inter hemispherical activities for two related classes of bimanual activities, with the ambition that this methodology can be adopted as a bimanual rehabilitation strategy. To achieve this goal, we collected data from a healthy sample during both bimanual task execution and resting state. We extracted EEG features as Power Spectral Density (PSD) and Cross Power Spectral Density (CPSD), in four frequency bands: relating power and connectivity between two signals. The results presented in this work correspond to resting state and

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Bimanual activities for healthy participants. EEG features of stroke survivors and healthy controls during resting state were reported in previous work [11] .

II. Procedure

Three main topics and areas were handled to develop this work. First one, was the developing of the game that recruits software engineering knowledge; second one, was the recruitment of participants and the acquisition of data supervised by an occupational therapist; and the final stage, comprises the processing and analysis of the collected data.

A. VR scenario (The Butterfly catcher - Bimanual Game)

The VR scenario was developed in the Unity3D Software [12] and uses a camera-based tracking software to capture the user upper limb movements [13]. The scenario was designed an infinite runner type of game called Butterfly Catcher (Fig. 1), in which a butterfly net moves steadily forward while the player has move his/her arms on a table top to turn to the right or to the left to avoid obstacles and catch the butterflies. The game is configurable, and presents the same quantity of obstacles and butterflies appearing at random positions. The velocity of the player is modulated by the task performance, increasing the velocity if the player captures a butterfly (scores) and decreasing it if the player hits an obstacle. The game menu allows the configuration of the minimum and maximum velocities, the step size for the variation of the velocity, the ID for the player and the duration of the training session (Fig. 1).

The link between the game and the bimanual coordination task was achieved by using a wood control structure based on separate sliders and controls for each hand (Fig. 2). Two handles that act as controllers are tagged with a unique tracker pattern and are attached to the sliders, which allow only forward and backward movements. A webcam-based tracking software, AnTS [13], was used to translate the movements of the hands to the lateral displacements of the butterfly catcher.

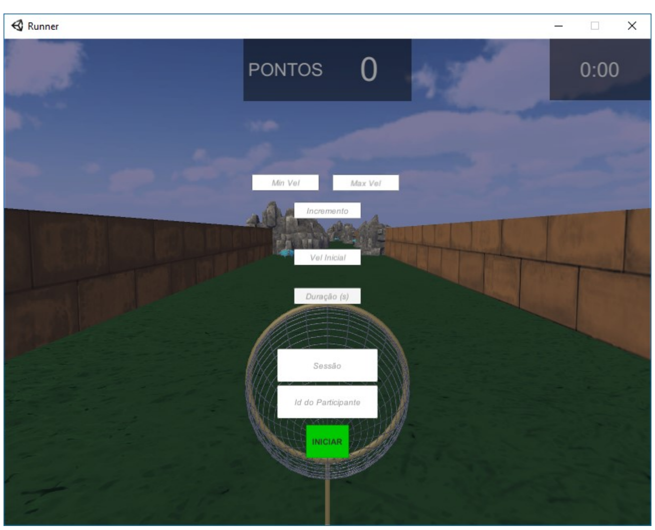

Fig. 1. Configuration of Butterfly Catcher Game

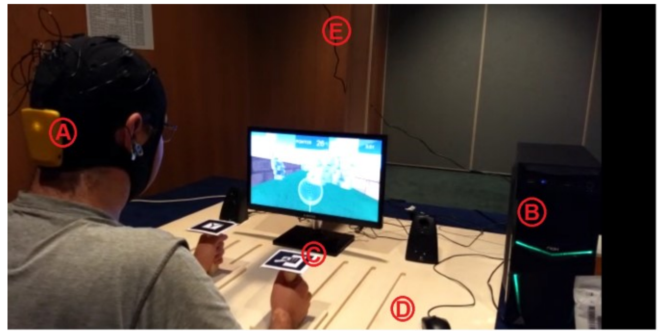

Fig. 2. Physical setup including A. EEG system; B. Computer; C. Tags for being tracked; D. Wood surface structure; E. Tracking Camera (not visible in the image)

As described before, the butterfly net advances in the x axis direction with a variable velocity according to the performance of the player. Lateral movements, right and left, are restricted between -3.5 and 3.5 in the z axis, where 0 is the center and 3.5 and -3.5 are the limits of the scenario. The lateral movement of the net is computed normalizing the physical range of movement for each participant to the (-3.5 – 3.5) range. In this way, to move the net to the left corner (-3.5), the player should move the left handle all the way forward and the right handle all the way backward, comprising of his/her maximum physical range of movement. The opposite physical movement will result in the net moving to the right corner. The movement of the net is the difference of the positions of the wood controllers:

$$Z = \text{Left} - \text{Right} \quad (1)$$

All VR gaming sessions were logged in real-time, including: the velocity, score and position of the net inside the game and the position of both real-world wood controllers.

B. Data collection

A healthy sample of 16 people (9 Males, 7 Females, age of 28.94 ± 5.12 years old) were recruited, all of them right handed. To participate in this experiment, volunteers could not have a clinical history of neurological conditions. Electrophysiological data was recorded with an EEG Enobio 8 wireless system at 500Hz (NeuroElectrics, Barcelona, Spain), placing the electrodes around primary motor and somatosensory cortices following the 10-20 system, with electrodes FC5, CP5, C3, C1, C2, C4, FC6, and CP6. EEG was recorded for three minutes under resting state, and for five minutes during the VR gaming session.

C. Processing and Analysis of Data

EEG pre-processing was performed using Matlab [14] with a custom developed tool based on EEGLab functions [15]. Filtering was done in the frequency band from 1 to 40 Hz, employing low-pass and high-pass Chebyshev filters, applying a forward-backward strategic filtering [16] to avoid non-desired effects in the phase of signals. Rejection of blinking artifacts was done visually supported with the identification of epochs that overshoot a threshold of 250µV in more than one channel. Epochs affected by blinking or movement artefacts were excluded from the analysis. After pre-processing, 6 datasets had to be excluded because more than 60% of the total epochs exceeded the threshold and keeping these datasets with a low quantity number of epochs would lead to a reduced statistical power after average with lower Signal Noise Ratio. The remaining final set of data was from 10 participants (7 Males, 3 Females, 29.9 ± 6.21 years old), all of them right handed.

Data alignment for upper limb movements and EEG recordings was done based on the real-time logging and interpolation of the movement signal from a variable sampling frequency of 50 Hz to the frequency of 500 Hz of the EEG acquisition. The detection of the bimanual movement events was based on the zero crossing of the *z* position signal (differential position signal) in the VR game scenario, and the derivatives of each control signal. Bimanual events were found in windows of time of one second, with only one event per window, being discarded windows with more than one event. Bimanual events were categorized in two sets, Left to Right (L2R) movement (Right handle forward and Left handle backward movements) and Right to Left (R2L) movements (Right handle backward and Left handle forward movements).

The full data set for EEG analysis is comprised by three different states: resting state, L2R movements and R2L movements. Two features were extracted (PSD and CPSD) in four frequency bands: Delta (1 - 4 Hz), Theta (4 – 8 Hz), Alpha (8 – 12 Hz) and Beta (12 – 30 Hz) in two groups of electrodes for PSD: Left and Right Hemispheres. Three groups of interconnectivity couples for CPSD were computed Intra-hemispheric Left, Intra-hemispheric Right and Inter-hemispheric. Interconnectivity couple groups are shown in Fig. 3.

PSD and CPSD were chosen as features to describe the differences between bimanual movements and resting state. PSD is used to characterize the power of the signal, where it is expected to find changes on the selected frequency bands between resting state and movement. Also, there could exist changes in power for the two different bimanual movements depending on the handedness of the population of this study. CPSD is used to quantify the cross-correlation between two signals. Therefore, it can index the intra-hemispherical and inter-hemispherical relations for neuronal activity recorded by the electrodes. PSD and CPSD were calculated using Hanning windowing method with 50% overlap and length of a window of 1 second.

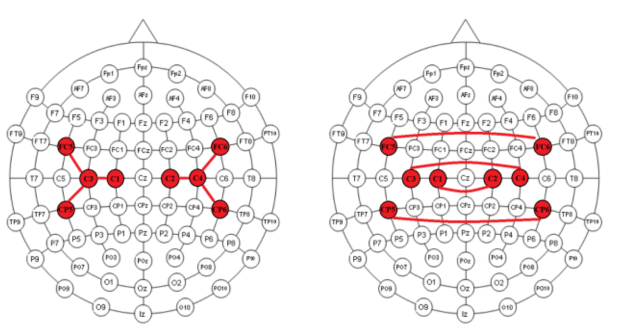

Fig. 3. Electrode coupling groups. Left. Intra-hemispheric short. Right. Inter-hemispheric

All data comparisons were statistically tested using R software [17] with a double tailed t-tests and p-values as outcome for the comparisons. The level of significance was set to p=0.05, because applying a Bonferroni correction would increase substantially the probability of Type II errors.

III. Results

In this work we studied the differences in EEG power and connectivity in a right handed sample of 10 healthy subjects, under resting state and bimanual movement through a gamified VR scenario. Multiple comparisons were made with the collected datasets. For PSD, we compared Resting state vs L2R vs R2L x in 4 frequency bands x 2 hemispheres (3x4x2), resulting in 24 scenarios. In addition, we also compared left vs right hemisphere activity for L2R and R2L events in the same four frequency bands (1x2x4), what resulted in a total of 32 comparison scenarios for PSD. Meantime, for CPSD we compared Resting state vs L2R vs R2L x in the same frequency 4 bands x 3 groups of couplings (3x4x3), totaling 36 scenarios, plus the comparison Left vs Right Intra-hemispheric activity for L2R and R2L events again in the four bands (1x2x4) for a total of 44 comparison scenarios for CPSD. Hence, the total of comparisons was 76, 32 for PSD plus 44 for CPSD.

The CPSD analysis indicated significant changes in functional connectivity between Resting state and bimanual movements in Delta Band for Intra-hemispheric connectivity in the Right Hemisphere ($CPSD_{REST}$ = 3.74±3.29 $\mu V^2/Hz$, $CPSD_{L2R}$ = 8.97±3.89 $\mu V^2/Hz$ with p=0.005 for Rest vs L2R and $CPSD_{R2L}$ =7.35 ±3.12 $\mu V^2/Hz$ with p=0.021 for Rest vs R2L), as is shown on Fig. 4. Also, significant differences were found for inter-hemispherical connectivity with $CPSD_{Interh}$ = 10.78±7.47 $\mu V^2/Hz$, $CPSD_{REST}$ = 3.60±2.35 $\mu V^2/Hz$, p=0.015 for Rest vs L2R.

The use of the CPSD feature was successful in identifying differences in functional connectivity between Resting state and bimanual movement events in the Delta frequency band. Connectivity plots (Fig. 5) are normalized to the maximum and minimum values, to facilitate the visualization of the differences.

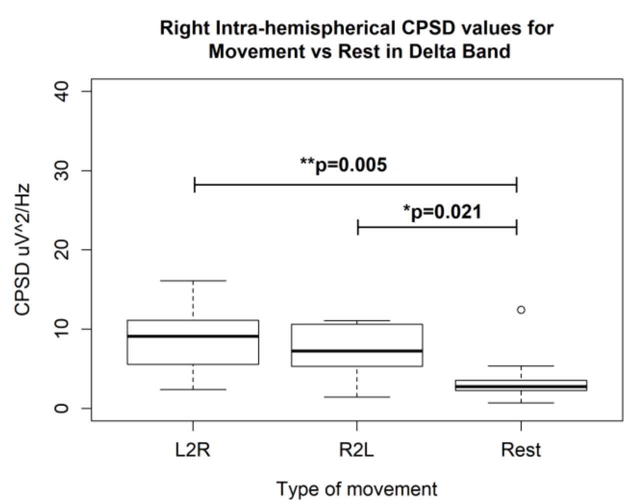

Fig. 4 Right Intra-hemispherical CPSD values for Movement vs Rest in Delta Band

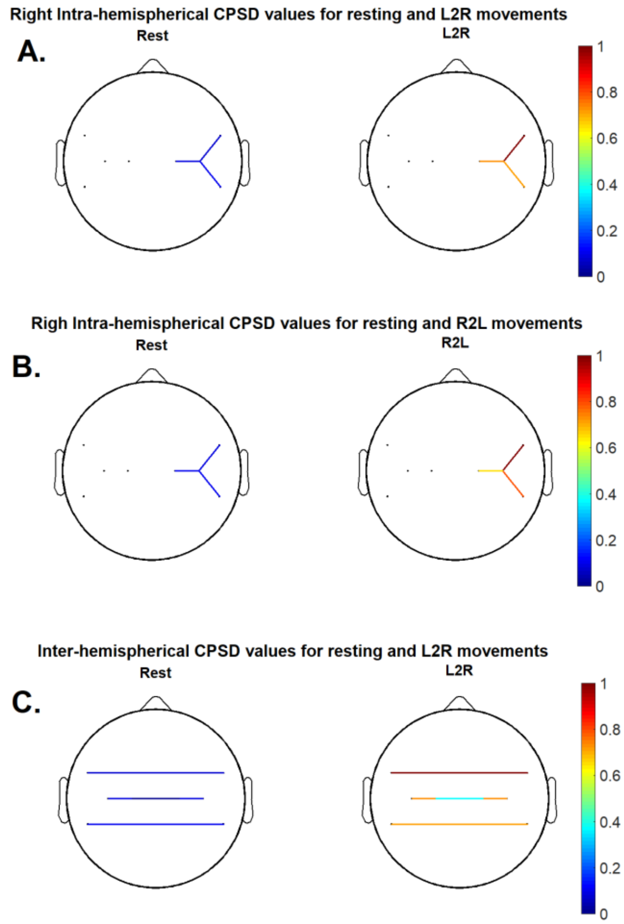

Fig. 5. Connectivity quantified with CPSD in resting and Bimanual movements. A. Intra-hemispherical Rest vs L2R, B. Intra-hemispherical Rest vs R2L, C. Inter-hemispherical rest vs L2R.

Theta band also showed significant differences between resting state and bimanual movements for Inter-hemispheric with p=0.03 for both cases with $CPSD_{REST}$ = 1.06±0.27 $\mu V^2/Hz$, $CPSD_{R2L}$ = 1.49±0.47 $\mu V^2/Hz$, $CPSD_{L2R}$ = 1.81±0.91 $\mu V^2/Hz$.

We found differences in PSD between Resting state and both bimanual movement events, specifically in the Delta band in both hemispheres. PSD values at rest were lower than during movement, with PSD_{REST} = 15.89±8.63 $\mu V^2/Hz$, PSD_{L2R} = 45.52±33.93 $\mu V^2/Hz$, and PSD_{R2L} = 48±39.28 $\mu V^2/Hz$ for Left Hemisphere, getting p=0.023 for L2R vs Rest, and p=0.03 for R2L vs Rest. Meanwhile on Right Hemisphere PSD_{REST} = 22.8±18.84 $\mu V^2/Hz$, PSD_{L2R} = 47.11±20.36 $\mu V^2/Hz$, and PSD_{R2L} = 45.54±39.28 $\mu V^2/Hz$ for Right Hemisphere, getting p=0.013 for L2R vs Rest, and p=0.019 for R2L vs Rest, as it can be seen in Fig. 6.

Similarly, there was a relevant difference in Theta for Left Hemisphere between resting state and L2R movements with PSD_{REST} = 5.03±0.82 $\mu V^2/Hz$, PSD_{L2R} = 3.73±1.71 $\mu V^2/Hz$ for a p=0.05.

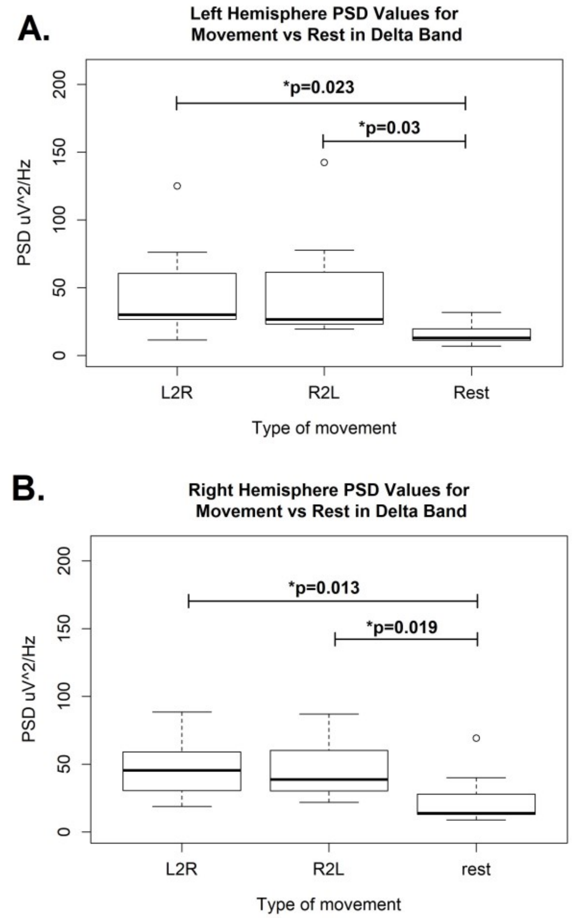

Fig. 6. PSD in Delta Band for under resting state and bimanual movements. A. Left Hemisphere B. Right Hemisphere

No other EEG power or connectivity differences were found for the remaining groups of comparisons.

IV. Discussion

In this paper we presented an analysis of power and functional connectivity of neuronal activity recorded with EEG electrodes over primary and somatosensory cortices. We studied differences between Resting state and two kind of bimanual movements, while the volunteers were playing an interactive VR game in which the movements of their arms were translated to the control of the lateral displacements of a VR element. Interestingly, results showed differences between bimanual movements and Resting state were mainly identified in the Delta frequency band, whereas sensory motor rhythms – the signature of motor actions – are expected in Alpha and Beta bands [18]. Significant differences for Delta band between bimanual movement and resting state showed that power is increased for lower frequencies in motor areas, which highlights the importance of the use of low frequency components to describe neural activity during movement. Similar approaches have been used in other studies for reaching and grasping movements [19], wrist movement [20], movement intention on slower frequency range [0.1 – 1 Hz] [21].

The results revealed no differences for connectivity (CPSD) or power (PSD) between the two types of bimanual movements used in the experiment, Right to Left and Left to Right, which corresponded to moving the left hand forward and the right hand backward, and vice versa. These results show that primary motor and somatosensory cortices are activated similarly and simultaneously if there is a bimanual movement. Translating this to the design of applications in BCI, it means that if only electrodes placed over the motor cortex are used, there should not be an effect of handedness of the player. However, it should still be possible to detect bimanual movements, but it may not be possible to detect differences between different classes of bimanual movements. To test if there would exist differences on neuronal activity for each hemisphere between the two bimanual movements related to handedness, it may be necessary to acquire data also from more areas of the brain with a different electrode arrangement than the one used in this study.

The lack of statistical differences in power (PSD) and connectivity (CPSD) between the two tested types of bimanual movements can be used as benchmark when this methodology is applied in a long term intervention to people with stroke suffering from lateralized motor deficits. Hence, in this case an initial asymmetry may be expected but also to be reduced throughout the recovering period. Nevertheless, it would be necessary to further study bimanual rehabilitation tasks with EEG and/or other neuroimaging techniques.

In this work were done multiple comparisons to study neuronal power and coupling in motor areas.It is necessary to take into account that we set the significance level to 5%. Our selection for this significance threshold is due to its exploratory nature and to avoid the increase of Type II errors probability, it was not used a more conservative methodology for correction as Bonferroni. . Finally, cross-correlational analyses between the signal of arm movement and EEG activity were all non-significant, meaning that the EEG patterns found cannot be explained in terms of movement artefacts.

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