Exploring the Potential of EEG for Real-Time Interactions in Immersive Virtual Reality

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Abstract: - Brain-computer interfaces (BCIs) can use data from non-invasive electroencephalogram (EEG) to transform different brain signals into binary code, often aiming to gain control utility of an end-effector (e.g mouse cursor). In the past several years, advances in wearable and immersive technologies have made it possible to integrate EEG with virtual reality (VR) headsets. These advances have enabled a new generation of user studies that help researchers improve understanding of various issues in current VR design (e.g. cybersickness and locomotion). The main challenge for integrating EEG-based BCIs into VR environments is to develop communication architectures that deliver robust, reliable and lossless data flows. Furthermore, user comfort and near real-time interactivity create additional challenges. We conducted two experiments in which a consumer-grade EEG headband (Muse2) was utilized to assess the feasibility of an EEG-based BCI in virtual environments. We first conducted a pilot experiment that consisted of a simple task of object re-scaling inside the VR space using focus values generated from the user's EEG. The subsequent study experiment consisted of two groups (control and experimental) performing two tasks: telekinesis and teleportation. Our user research study shows the viability of EEG for real-time interactions in non-serious applications such as games. We further suggest that a simplified way of calculating the mean EEG values is adequate for this type of use. We , in addition, discuss the findings to help improve the design of user research studies that deploy similar EEG-based BCIs in VR environments.

Key-Words: - electro-encephalography, EEG, interaction, locomotion, user research study, virtual reality

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1 Introduction

Immersive experiences offered by VR and augmented reality (AR) are gaining traction in areas outside gaming and simple simulations [1]. However, in tasks that require elevated levels of concentration, such as teleoperated robotic machinery [2], remote medical treatment and education, virtual content can distract users if it is not on par with their attentive state [3]. The most common solutions for user control in commercial VR devices are physical controllers and hand or body tracking [4], [5]. In addition, the most common feedback modalities are visual, audio, and haptics (vibration). Capturing the user's attention using options derived from what is available can be challenging in six degrees of freedom (6DoF) or 360° virtual environments. Various studies have explored the use of multimodal feedback to help govern the attention of the user while BCIs have also shown promise with respect to the potential use of brain signals as a controller [6], [7], [8], [9].

Using electroencephalography (EEG) as a controller is not a novel idea in VR research [10], [11], [12] but having emerged only recently, user studies are scarce as devices using wireless dry electrodes are very sensitive in regards to their correct placement and they also remain susceptible to inference. Against this backdrop, our experimental setup consists of a popular head mounted display (HMD) along with a portable EEG device, delivering both user comfort and easy electrode setup. This first experiment was a pilot study with six participants where our main focus was to assess the feasibility of our setup. This was done by measuring user comfort while subjects were exposed to closed-loop biofeedback given through a virtual heads up display (HUD) shown in VR. The pilot study consisted of a simple task of re-scaling an object in the VR realm using only the user generated EEG signals. In the second experiment, the system architecture was simplified to lower the latency caused by the EEG data conversion. This experiment featured two tasks: telekinesis and teleportation. In the telekinesis task, users were instructed to move objects to predetermined locations inside the VR space. Respectively, in the teleportation task, participants were instructed to move along a course of checkpoints set in VR using the teleportation utility. In both tests, the actions such as grab, move, and locomotion, were controlled using the portable EEG device. We also had a control group who wore the EEG device, however their EEG values were not used as a control mode.

This article presents two experiments, pilot experiment (see Subsection 3.1) and study experiment (see Subsection 3.2), in which some of the controls are bypassed with a commercially available non-invasive EEG based BCI, enabling users to have direct agency in the simulated environment. Strict policy for social distancing was in place due to the Covid-19 pandemic when the study was planned and conducted. Specifically, we adapted the user study for a smaller sample and used within-subject design. The testing was conducted in three different locations during April 2021. Each of these locations had their own observer and researcher running the experiments. The protocol for testing was decided well in advance to keep the procedure uniform. Still, when conducting testing in different locations and with a different set of equipment, the comparability of the results is a concern [13]. For all testing, the VR equipment and Muse 2 headsets were the same models, but not the same exact units. The PCs used for running the simulations were very light weight, all the computers were able to run at the intended framerates. This was made possible by improvements made over the proof-of-concept pilot experiment, which was run with a similar setup and devices, but with a slightly more complex system architecture and a less polished VR space. For analysis a non-parametric Kruskal-Wallis test [14] was used for results of the questionnaires while the completion times were analyzed with one-way ANOVA. User research study progress is presented in Fig. 1.

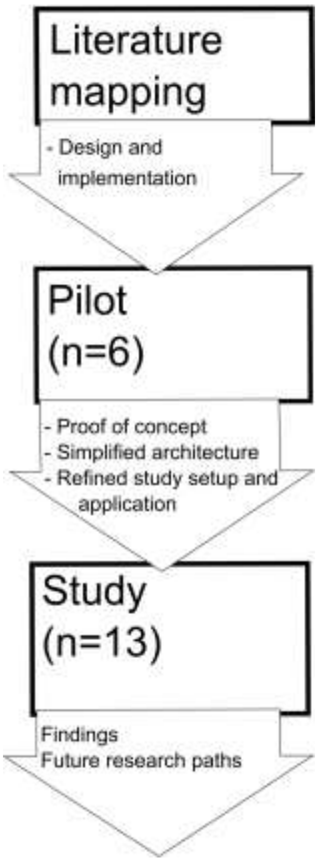

Fig. 1: User research study progress.

The purpose of this study was to explore the feasibility of a consumer grade EEG as a controller in immersive VR and gain some early insights on user experience (sense of agency and cyber sickness) when using EEG for locomotion and interactions. Our findings show that a simplified approach can be adequate for non-serious use.

This paper is structured as follows. First, in Section 2, we introduce related work and rationale behind this study. Then, in Section 3, we describe the research study beginning with the pilot experiment description and continuing to the study experiment. This section also describes the architecture of our system, procedure and the demographics of our test users. In Section 4 we go through the results and analysis methods of this mixed methods study. Discussion of the observed results is performed in Section 5, while the research effort is concluded in Section 6.

2 Related Work

Naturally occurring forms of interaction, that bypass the traditional physical inputs such as the keyboard and the mouse, have for some time been core topics in human-computer interaction (HCI) [15]. Recently, institutional interactions that involve a combination of voice, eye-tracking, and hand gesture controls have become the industry norm for top-tier mixed reality (MR) devices like the Microsoft HoloLens 2 [16]. While the mouse and keyboard combination might not be replaced in the near future, other modalities and controls are essential in achieving the true potential of immersive VR [2], [3], [17]. EEG-based BCIs in VR have been used as replacements for the typical game controls [12], [18], enabling dynamic and responsive training environments driven by task customization and adaptability [19]. EEG data has also been used to better understand disorientation and physical discomfort [20], [21], [22], brain activity during navigational tasks [21], and as an attention enhancement [11].

Although EEG systems are mostly used in conjunction with other data gathering methods [20], [21], [22], [23], [24], EEG data has been instrumental in measuring the cognitive load of users [23], [24]. Consequently, this body of research has clear implications for improving VR design. For instance, the connection between locomotion in immersive VR and cybersickness [25], also known as VR sickness, has been studied in the past using VR-native interactions like teleportation, gaze, free locomotion, tracking combined with non-isometric walking etc. [26], [27]. Within this context, prior VR research has leveraged portable EEG devices as a noninvasive BCI for evaluating virtual interactions including locomotion [10], [28]. Similarly, proof-of-concept systems that integrate a BCI and VR headset have been developed, targeting improved mindfulness in immersive environments [29].

Portable devices such as Emotiv EPOC, Muse 2, and NeuroSky MindWave have sparked renewed interest across research fields [30], [31]. In particular, Muse 2 [32], is a light-weight portable EEG headset, which has been validated against large-system EEG setups for both continuous recording of EEG data and in event-related brain potentials (ERP) research [33]. As reported in the literature [34], the Muse EEG system has been used to detect the brain states for concentration and relaxation [29], [35], task enjoyment [36], pain [37], as well as detecting the cognitive state of the user [38]. In this study we explore the use of EEG as an additional mode of interaction. The goal of the technical implementation was to use consumer devices and measurement solutions that would provide usable EEG data as close as possible to real-time.

While using EEG can improve some aspects of the user experience, VR can also influence the EEG measurements by offering a dynamic and immersive scene for feedback [6], [39]. BCIs connected with VR can result in fewer errors due to enhanced mental effort [40]. This suggests EEG can improve the engagement and focus on the users in VR. In this research effort we were interested in the little explored connection between VR sickness and EEG-enabled locomotion. In addition, we targeted an even less explored aspect in using EEG as a mode of interaction, for a sense of agency. We did this based on the assumption that due to higher immersion and focus there might be observable differences in this context of user experience.

Experiments using immersive technologies (e.g., VR, AR, MR, XR) are usually conducted in controlled environments and suitable research facilities. As in other fields, the Covid-19 pandemic has forced educators and researchers to work remotely and to social distance at the workplace. This has severely hampered user testing for the devices and simulations. Covid-19 has also raised new concerns especially regarding the cleanliness of the equipment, when conducting experiments where the devices are passed on from person to person numerous times in short periods of time [13].

3 The User Research Study

We conducted a user research study to explore the potential of using EEG data as a controller i.e., a mode for interaction in immersive VR. The study experiment (see Subsection 3.2) was preceded by a pilot experiment (see Subsection 3.1) that we briefly describe in the text below.

3.1 Pilot Experiment

The pilot experiment took place pre-Covid-19 in November 2018 and it aimed at validating the setup of using an HMD, Oculus Quest, together with a Muse 2 and providing accurate data collection. Muse 2 sends raw data on five bands one of which is ground as presented in Fig. 2. The remaining four bands correlate to four locations on a normal EEG cap which would contain 10 – 20 sensors. Muse 2 is also cordless, delicate and lightweight, which makes it possible to fit in under a VR HMD. On average, each band sends 255 values per second which are then fast Fourier transformed once every second to obtain the final window of EEG values. The frequency in this window is from 1Hz to 128 Hz with a time resolution of one second. The resulting frequencies correlate to the microvolt values sent by Muse 2. We consider these values to be relatively only to each other in an ongoing measuring session, because skin conductivity varies from person to person and a number of factors can cause interference to the measurements and the Bluetooth connection. This architecture in the pilot experiment was more complex than in the study experiment (see Subsection 3.2). This is because in the pilot experiment equipment consisted of a controller PC, a Raspberry Pi, a Muse 2, a HDM, and a Polar H10 heart-rate sensor. It was simplified for the actual study by using Bluetooth to connect Muse 2 to the PC instead of Raspberry Pi, and adjusting the calculations for transforming EEG signals into usable data. The Polar H10 heart-rate monitor was not used again in the study, since it did not add value in the analysis. Intuitively, the Quest HMD was also replaced with Oculus Rift S.

Six subjects participated in the pilot experiment, see Fig. 3. They wore a Muse 2 accompanied by a Polar H10 heart rate sensor [41], that was attached to the chest using a strap. Oculus Quest was used as the HMD. The participants were asked to perform an object scaling task. Three participants, group 1 (G1), were exposed to their data through a virtual wrist-mounted heads-up display (HUD). The other three participants in the second group, (G2), were treated similarly, but without the exposure to the HUB. Both groups consisted of one female and two male subjects, aged between 22 to 40 years of age. All subjects were students with a computer science and engineering background. One was majoring in pedagogy and one in geography. Informed consent was obtained for the students prior to experiment. The subjects were told how Muse 2 works and that they would be able to rescale an object (ball) projected in the VR-scene using EEG data. Following a short guidance session in the VR play area, the participants were asked to relax for 60 seconds with their eyes closed while the threshold values were being collected. The participants in the first group were asked to open their eyes, and while focused, instructed to scale the ball. The group was provided with a virtual wrist-worn HUD, displaying data from Muse 2 (EEG) and the heart-rate monitor. The participants in the second group repeated the same tasks, but without having the HUD data visible. On average, the task lasted two minutes. The experience in VR consisted of a simple scene, with a hovering ball in the user's vicinity. The size of the ball changed depending on the focus level of the user. After the experiment, participants in both groups were asked to fill out a questionnaire. The pilot experiment was conducted at the university campus using a semi-CAVE, that provided a calm and isolated environment, void of distractions that could have influenced the EEG measurements.

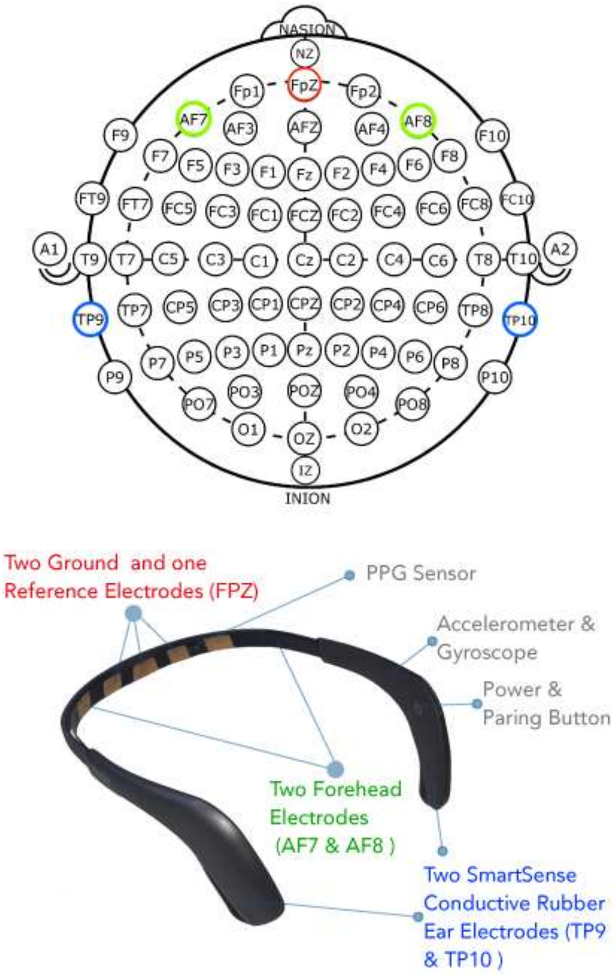

Fig. 2: The topological arrangement of electrodes based on the 10 – 20 standard (top) and the Muse 2 headband (below).

3.2 Study Experiment Setup and Procedure

The study experiment took place during spring 2021. Due to restrictions caused by the Covid-19 pandemic, the study experiment was conducted in three separate locations with 13 participants who were either friends or family of the researchers. While this may have introduced bias, it is also possible that this allowed the participants to feel more relaxed and comfortable during the experiments. This in turn would have been important especially with regards to the collected EEG data. The participants had a wide variability in their age distribution, from 21 to 58 years of age (M = 35.5, SD = 15.7).

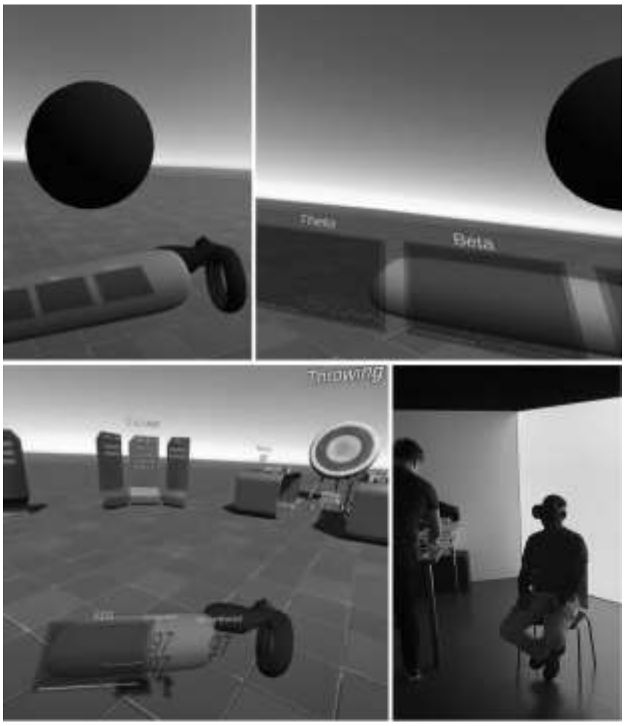

Fig. 3: Pilot experiment of the research study. Top images show, from different angles, the virtual environment where the scaling task took place. This is the game view seen by the group that was exposed to the closed-loop system with the wrist-worn heads-up display (HUD). Images below on the left show a play area used by the participants to get familiarized with the virtual environment. Image below on the right shows the semi-CAVE environment used in the pilot experiment.

Each location had its own observer and researcher running the experiments. The protocol for testing was planned and rehearsed in advance. In our case, the VR equipment and the Muse 2 headset used were the same models, albeit not the same exact units. The VR scenes, Table 1, were run on different PCs, however, the simulation itself being very light weight, meant that all the computers were able to run at the intended high framerates. Still, when conducting tests in different locations and with a different set of equipment, the compatibility of the results is always something you have to consider [13].

The equipment in the study experiment included an Oculus Rift HMD and a Muse 2 EEG headset. Unity development platform was used to create and run the simulations. Blue Muse software created by Kowaleski and Wicklund [42] was used to connect Muse 2 to a PC. We simplified the architecture by removing the Raspberry Pi and using Lab Streaming Layer (LSL), thereby Muse 2 could stream the EEG data to Unity directly. BrainVision LSL Viewer [43] was used to observe the EEG channels simultaneously. It was also used in calibrating Muse 2 before running the experiment. Based on the pilot experiment and further testing with Muse 2, it was determined that the placement of the unit on the participants' heads with the HMD had to be precise and even slight changes in the position could produce errors or more interference. Since the participants wore Muse 2 under the HMD, the calibration phase was as interference-free as possible.

Table 1. Description of the different VR-scenes and user tasks used in this study experiment. All participants went through the tasks in the same order they are in this table. The only difference between experimental and control groups was that the control group generated fake focus values.

Setup	Purpose
Playroom	Calibration and familiarization with some EEG-mediated interactions
Teleportation	Test the use of teleportation
Timed teleportation	Test the use of teleportation with a 180 second time limit
Puzzle room	Interacting with objects using EEG, grabbing and dropping.

We use a simple way of calculating the focus values by taking the four data channels from Muse 2, first summing up the channels and then dividing the sum by four with a frequency of 10Hz. These averages are then transformed into the focus values by using standard deviation for every 100 average samples at a time. The calculation works within a first-in-first-out principle for the averages. So, each time a new average is added into the buffer, the oldest one is dropped and then a new focus value is calculated. This helps in keeping the focus value transition smoother, as calculating the focus values from a new batch of data every time could induce very abrupt changes in the value.

The participants were divided into groups based on study experiment conditions. Due to the limited availability of test users, we conducted a within-subjects experiment in regards to the VR setup, however the experimental and control groups were separated. The experimental group tested with actual focus values that were generated from the users' EEG data, while the control group did the same tasks but with randomly generated fake focus values.

Table 2. Completion of mean focus values of control and experimental groups. Values were calculated as a mean value from the four channels of the Muse 2 with a frequency of 10Hz.

Setup	Control (x,σ)	Experimental (x,σ)	p-value
Playroom	(0.39, 0.41)	(2.10, 0.87)	0.004
Teleportation	(1.23, 1.63)	(4.11, 1.19)	<0.001
Timed Teleportation	(0.96, 1.10)	(4.22, 0.97)	<0.001
Puzzle room	(0.27, 0.29)	(3.54, 1.18)	0.004
Whole course	(1.13, 1.28)	(3.94, 0.48)	0.007

The VR scenes tested were presented in Table 1, as: (1) Playroom, (2) Teleportation, (3) Timed Teleportation, and (4) Puzzle room. All these scenes were tested by both the experimental and control groups. The Playroom contained objects that the users could interact with by using the telekinesis system. This room was used to teach the user how they are able to move the objects by focusing. In the Puzzle room, the users used the telekinesis system to place certain shaped objects to their corresponding positions. These positions were indicated by table-shaped pedestals. The pedestals changed their color to green when the correct object was placed on them. When all objects were in their correct places the task was completed. The Teleportation scene is a hallway with five nodes. In this scene the users had to use the teleportation system to teleport into the nodes using their EEG. The task was completed after the user had teleported through the sequence of nodes. Timed Teleportation used the same scene but with a 180 second time limit, EEG values and completion times were recorded from all the mentioned tasks.

4 Results and Analysis

The collected material consisted of EEG data, completion times, general observations and questionnaires. The pre questionnaire had a consent form, demographic questions, and questions on susceptibility to motion sickness. The post questionnaire contained a simulator sickness questionnaire (SSQ) [44] and questions about sense of agency adapted from [45].

The EEG for the participants was recorded from all the scenes. The focus values were determined using the method detailed earlier. The recorded EEG mean focus values were <0.050. For completion times we had less data, therefore a Kruskal-Wallis test was used to analyze the results, as presented in Table 2.

Table 3. Statistically significant results on mean completion times and variance in seconds.

Setup	Control (x,σ)	Experimental (x,σ)	p-value
Playroom	(62.01, 35.68)	(223.58, 161.42)	0.045
Timed Teleportation	(79.01, 12.38)	(69.61, 25.82)	0.032
Whole course	(297.75, 62.12)	(496.36, 148.50)	0.022

As with the focus values and EEG, the completion times were collected for all of the tasks. The only statistically significant results were found in completion times for Playroom and Timed Teleportation as well as total completion for the whole course. The whole course consists of all the tasks including the Playroom scene, as presented in Table 3.

After conducting a Kruskal-Wallis test [14] on the SSQ results, we did not find any statistically significant differences between the groups. Therefore, only the total simulator sickness values are reported here, as presented in Table 4, and not the subcomponents from the original questionnaire.

Table 4. Statistically significant results from SSQ.

Group	Measure	Mean rank	Variance	p-value
Control	Total Simulator Sickness	33.66	581.88	0.283
Experimental	Total Simulator Sickness	20.83	190.49	0.283

The post-questionnaire also contained statements mapping the participants' sense of agency in the VR. This questionnaire was loosely based on [45] and the analysis was conducted using a Kruskal-Wallis test [14]. The purpose of this questionnaire on agency was to observe differences mainly in the telekinesis use case. However, the only close to significant results were found in the Teleportation task, as presented in Table 5. Concretely, questionnaire given to users had five specific questions, such as: (1) "Q_1 = I was able to interact with the environment the way I wanted to", (2) "Q_2 = The teleportation task was (1 difficult, 7 easy) to perform", (3) "Q_3 = The color of the objects reflected my level of concentration accurately in the teleportation room", (4) "Q_4 = Did you gain enough feedback for your actions in the teleportation room?", and (5) "Q_5 = I felt the time limit affected my performance in the teleportation room".

Table 5. Results from the post-questionnaire section measuring sense of agency for the teleportation task where the results were close to being statistically significant. (*Note:* Q is the abbreviation for "Question").

Category	**Q**	**Control** (x, σ)	**Experimental** (x, σ)	**p-value**
Teleportation	Q_1	(6.0, 0.89)	(4.85, 1.57)	0.071
	Q_2	(5.83, 1.32)	(4.85, 1.57)	
	Q_3	(5.16, 2.13)	(4.57, 0.97)	
	Q_4	(5.33, 1.75)	(5.42, 1.61)	
	Q_5	(5.33, 1.03)	(4.85, 1.86)	

4.1 Other Observations

After answering the post-questionnaire, the participants were told which group they had been a part of. Some who belonged to the control group that used fake focus values, reported that they had become suspicious especially about the telekinesis system. They said it seemed difficult to drop the objects and that they had thought it could be because they had had a tiresome day. In the experimental group some participants reported they had discovered a way to easily release the objects by blinking. This is commonplace with EEG devices having interference from the movement of facial muscles. One person in that group also said they could increase their focus value more easily if they concentrated on looking at the edges of an object instead of looking straight at it.

Participants in both groups reported they found the focus features interesting and entertaining. Most of them thought that these types of features can enhance the immersive experience of VR. The participants with eyeglasses had a disadvantage in the tasks, because it was not possible for them to wear their glasses under the HMD and Muse 2. They reported that it was at times difficult for them to see the objects in the scene.

5 Discussion

In this small-scale user research study, we coupled a commercially available EEG device, Muse 2, with an HMD in order to explore the suitability of using brain signals as an alternative for the more traditional controllers in immersive VR. Our focus value calculation is based on standard deviation, which is an overly simplified way of using the EEG data and not an accurate representation of the volume of focus. This however, was enough for our test users to have a mainly positive experience, which would suggest that for games and entertainment purposes real-time EEG could be a useful addition. If the target would be to use focus as a mode of interaction, more sophisticated solutions may be needed as even in this study experiment blinking caused a peak in EEG values, and the users learned this quite quickly.

When comparing the focus values, it seems the participants in the experimental group succeeded better in keeping their focus level higher. This suggests that the experimental group needed to stay focused, while the control group was able to pass the tasks with the help of the "fake" focus values i.e., by chance. In this case it is unfortunate that we cannot also show statistically significant results between the experimental and the control group in the post-questionnaire measuring sense of agency. In the Teleportation task, only agency had a p-value of 0.071, with the experiment group faring higher.

The reason for comparing the Teleportation, with and without a time limit, was to see if it would be easier for the participants to focus without a time limit. There was a statistical difference between timed and untimed Teleportation, but not in the way that we expected. People fared better in the time limited version of the test, and the reason for this was in hindsight obvious. The Teleportation scene without the time limit was run fist giving the participants an opportunity to not just learn the route but also to acquaint themselves better with the teleport system. Then, when it came to running the time limited version of the task, the participants were already aware of how the whole scene worked, and did not have to learn the teleport mechanics nor the route. This led to the users scoring better completion times in the time limited scene. The original idea for measuring completion times was to see if random values opposed to the actual values would influence the scene of agency of the test users especially in the tasks requiring interactions. However, we did not get significant results with such a small sample and therefore cannot compare results between experimental groups.

Since the results from SSQ were inclusive, we cannot say if there were differences between the groups. However, we did not observe much VR sickness with the participants to begin with. This is possibly due to teleportation being the most user-friendly mode of locomotion in VR [46]. This was also expected since in the designated tasks, other than the teleportation, the user did not need to move.

5.1 Limitations

There are many limitations in this study experiment. We run the tests in three different locations. In each location, the rehearsed testing protocol was used to ensure the results would be comparable to each other. However, while running tests in several different locations, even with mostly identical equipment, the comparability of the results is of concern [13]. As with the research locations, Covid-19 also forced limitations to the sample size and the pool of available participants. The tests simply could not be run in public with a large pool of volunteers due to health concerns. Instead the participants were people familiar to the researchers and the experiments were run in private. Conducting the testing like this can have positive and negative effects on the results. Positive in the way that the participants might feel more relaxed in the situation, which could make the collection of biometric data, such as EEG, more reliable. However, at the same time there is a chance of acquiescence bias. The participants were informed their honesty was valued more than favorable comments, but this source of bias cannot be completely ruled out. To mitigate this bias the purpose of the study experiment was revealed to and discussed with the participants only after the study experiment.

When interpreting our results, it is important to remember that while we speak of focus values, we used a commercially available EEG device and a very simple way of calculating the focus value. We also noticed that the EEG data recorded from Muse 2 is very sensitive to muscle movement. Muscle movement, blinking as well as eye movement, had a noticeable effect on the amplitude of the raw EEG sent by Muse 2 and it was easily observable from the recorded data. The method used for calculating the focus values was also simpler compared to the one used in the pilot experiment. Using standard deviation of averages instead of fast Fourier transformation was faster but in turn less accurate. Still there was an observable difference between the two groups, experimental and control. It is also notable that the false EEG was not random, the behavior of the participants was what brought the unpredictability to the setup in the control group.

5.2 Future Work

As the pandemic clears we hope to repeat this study with a bigger sample to verify our results and gain more conclusive results. We in addition conducted the study experiment using within subjects' setup to minimize social interactions due to the pandemic. This of course is not an ideal setup for a study like this.

EEG and the needed calculations for using it in real-time interactions in VR have their limitations. In future we would like to continue studying the optimal setup for a good user experience when using light weight EEG devices in VR, both in games and in serious applications. These applications have different requirements for accuracy in interactions. Our current setup with lossy communications and simple calculations might be useful for entertainment purposes, but other solutions are needed for more serious applications. Muscle movements on the forehand and around eyes caused disturbance to the signal and as we specified in the results the users were able to cause a peak in measurements by blinking. We can suggest the use of the current solution in certain types of future studies such as the intuitiveness levels of EEG controls in gameplay. Despite the inaccuracy in the data, when studying the relevant aspects of the user/player experience, it is plausible to suggest that the EEG controlling mode did work as intended most of the time and has potential for entertainment purposes.

5.3 Ethics Statement

We follow the ethical requirements established by the Finnish advisory board on research integrity (TENK) [47]. The gathered material has been handled and informed consent from the participants was obtained in accordance with Finnish and European laws. We also consulted and followed the guidelines of our local ethics board [48].

5.4 Declaration of Conflict of Interests

The authors declared no special conflicts of interest with respect to the research, authorship, and/or publication of this article.

6 Conclusion

In this small-scale user research study, we demonstrate the potential of EEG as a controller in less serious applications. We were not able to show that using EEG for locomotion would influence cyber sickness, however there were some slight differences in task completion times between control and the experimental groups suggesting that locomotion with teleportation using EEG was slightly faster in the experimental group where participants were able to influence the locomotion. It remains whether this was due to intuitiveness of the modality of higher sense of affordance, which made adaptation and learning faster, but we suggest exploration on this topic for future research.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Panos Kostsakos was responsible for conceptualizing and developing the methodology. Oskari Rajala, Mikael Sarkiniemi, Markus Hirsimaki, and Jere Kinnunen developed the software and pilot experiments. Mikko Koriakoski contributed to the original draft preparation and formal analysis. Theodoros Anagnostopoulos, Panos Kostsakos, and Paula Alavesa were involved in the writing, reviewing, and editing of the manuscript. Finally, all authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

The authors have no conflict of interest to declare that is relevant to the content of this article.

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