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REVIRE: A VIRTUAL REALITY PLATFORM FOR BCI-BASED MOTOR REHABILITATION

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ABSTRACT: We introduce REVIRE (REhabilitation in VIrtual REality), an immersive virtual reality platform for post-stroke upper limb rehabilitation with integrated EEG recording. REVIRE immerses users in a 3D virtual environment where they can practice motor tasks that reflect everyday activities while providing comprehensive performance data with synchronized hand trajectories and EEG signals. Our proof-of-concept study tested the application on four healthy individuals across multiple training sessions. We observed significant effects of training on performance, evidenced by reduced task completion times. Changes in performance coincided with a decrease in EEG sensorimotor activity, consistent with existing motor learning research. In addition, the low incidence of cybersickness reported by participants indicates a comfortable and user-friendly experience, making our setup suitable for patient use. Our preliminary findings demonstrate the suitability of our virtual reality platform for BCI-based motor rehabilitation for clinical environments and beyond.

INTRODUCTION

Stroke is a critical global health concern, resulting in significant motor deficits that heavily impact patients' quality of life. Upper limb (UL) impairments, in particular, severely limit patients' independence and ability to perform activities of daily living. Traditional therapy approaches that involve face-to-face, therapist-led physical exercise often fall short of fully addressing patients' needs. Constrained by limited financial and personnel resources, traditional hospital-based rehabilitation struggles to provide sufficiently engaging, intensive, and personalized therapy [1]. In response to these challenges, recent years have witnessed a surge in research on novel technology-based approaches aimed at making rehabilitation more effective, individualized, and accessible [2].
Brain-computer interfaces (BCIs) represent a significant innovation in this field. By providing direct feedback on brain activity, BCIs encourage patients to actively engage in the self-regulation of their neural states. This approach has been shown to promote neural plasticity and improve functional outcomes [3]. When combined with immersive virtual reality (VR) as a feedback modality, BCI-VR systems can provide ecologically valid environments for task-specific and intensive practice, controlled through the patient's brain activity [4]. Despite the growing demand for rehabilitation services that extend beyond hospital settings, the widespread use of BCIs is currently limited by the cost and complexity of the required hardware. Nonetheless, with recent advancements in VR technology, the application of BCI-VR outside the traditional clinical settings is becoming more feasible.
New generations of VR head-mounted displays (HMDs), such as the Meta Quest 2[1], have become lighter, more portable, and more affordable. A major advancement has been the implementation of full hand tracking, which monitors the movement of the entire hand, including all fingers, joints, and nuanced gestures. This allows users to interact with the virtual environment more naturally, without the need for controllers. It also provides clinicians with direct access to patient movement trajectories, a feature previously only available with high-end motion capture systems and robotic rehabilitation devices. In addition, newer HMDs have considerably reduced the incidence of cybersickness, the motion sickness-like adverse effects [5], which had been a concern for VR use in patient populations.
Recently, several rehabilitation games have been developed to leverage the advantages of contemporary VR-HMDs for post-stroke UL recovery. Mekbib et al. found that the addition of immersive VR UL training to occupational therapy resulted in significantly greater functional improvements compared to occupational therapy

[1]https://www.meta.com/at/en/quest/products/quest-2/

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alone [6]. Fregna et al. developed an immersive environment for telerehabilitation, incorporating a client app for real-time remote supervision [7]. Current BCI-VR applications predominantly employ the motor imagery paradigm to provide patients with feedback on imagined or intended movement [4]. However, emerging research suggests a potential for expanding BCI-VR paradigms. A study on BCI-VR for gait rehabilitation by Luu et al. observed an increase in cortical involvement during treadmill walking when participants controlled the virtual walking avatar via neurally decoded gait kinematics compared to when the avatar mirrored their actual steps [8].

In this paper, we introduce REVIRE, a novel VR application for post-stroke UL rehabilitation that features an immersive, easily customizable training environment. Our application supports comprehensive patient monitoring through full hand tracking and integrated EEG signal recording. Moreover, we employ commercially available low-cost VR hardware for utilization outside clinical or laboratory environments. We evaluated the feasibility of our setup with a sample of healthy participants. By collecting data across multiple recording sessions, we aimed to verify whether our system could produce viable data for assessing user performance and progress. We also sought to ensure that the setup was comfortable for users and did not induce adverse effects. In the following sections, we describe the game environment and tasks, the data collection methods, and the preliminary analysis results. We demonstrate that our application is well-suited for BCI-VR rehabilitation research, extending its potential use beyond clinical environments.

MATERIALS AND METHODS

REVIRE Design: We developed an immersive VR game using the Unity 3D game engine[2]. The source code is freely available on GitHub[3]. In the 3D environment, we created motor tasks that closely mimic everyday activities. We presented the game via the Meta Quest 2 HMD.

REVIRE Environment: The REVIRE environment is set in a home interior. Users are seated behind a table, both in the physical and in the virtual world. Before starting the tasks, they are guided through a calibration procedure that co-locates the physical and the virtual table. This ensures that users feel a physical sensation when touching the virtual table, thereby increasing the sense of immersion and presence.Virtual hands, seen from the first-person perspective, animate the users' hand and finger movements and enable them to interact with virtual objects.

REVIRE Tasks: The game consists of three functional motor tasks, shown in Fig. 1. In the *Pouring* task, users pour water from the bottle into the glass, filling it to a specified line. The task is completed when the bottle and the filled glass are returned to their respective starting areas. In the *Drinking* task, users are presented with a glass filled with water. To drink, they lift the glass towards their mouth and hold it at an angle until it empties. They complete the trial by placing the empty glass in a designated area on the table. In the *Box* task, a podium with three areas at different height levels is presented on the table, with a box placed randomly in one of the areas. Users hold the box with both hands to move it to the target position.

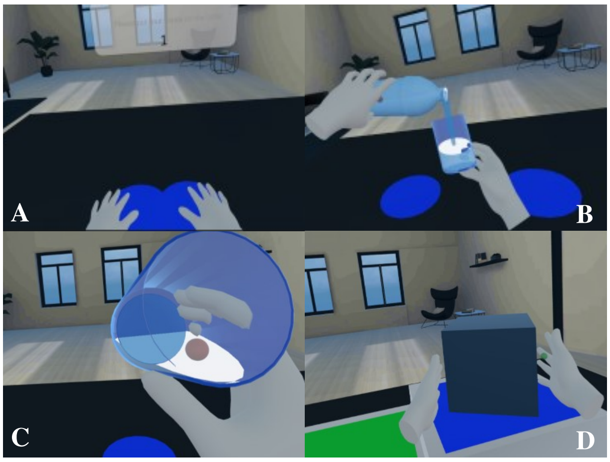

Figure 1: Gameplay: A - resting period, B - Pouring task, C - Drinking task, D - Box task.

Each task trial begins with a five-second rest period, which serves as the baseline for the EEG analysis. Users are asked to place their hands on the table and remain still while a countdown to the start of the task is displayed. Following the rest period, users are presented with the objects required to complete the task. The goal of each task is to accurately perform the intended action while minimizing the completion time. Users can perform the movements at their own pace and explore different movement strategies to complete the task. At any point in the game, they can reset the objects to their starting positions and continue the task without interrupting the trial. At the end of each task, they receive performance feedback through task completion times.

Participants: Participants were partially recruited using the Vienna Cognitive Science Hub Study Participant Platform, which uses the hroot software [9]. Four healthy participants, aged 54.0 ± 10.4 years (one female), took part in the study. All had normal or corrected-to-normal vision and little to no previous experience with VR. All participants gave written informed consent and were compensated for their participation. The study protocol was approved by the University of Vienna Ethics Committee.

Procedure: Participants attended four recording sessions over 10.0 ± 3.6 days. The total length of a session, including preparation time, was between 2 and 2.5 hours. Participants were seated comfortably behind a table for the duration of the recording. After EEG preparation, we placed the HMD over the EEG cap. The experimental setup is illustrated in Fig. 2. In the first session,

[2]https://unity.com/products/unity-engine
[3]https://github.com/praggam/REVIRE

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we instructed the participants on how to navigate in the virtual environment, and they completed a practice trial of each task. Sessions consisted of four blocks of the REVIRE game, each comprising 10 trials of every task (*Pouring*, *Drinking*, and *Box*, in this fixed order). EEG was recorded continuously during every block. The average duration of the VR gameplay was 39.4 ± 4.8 minutes, which is below the recommended maximum [10]. At the end of the session, participants completed the Virtual Reality Sickness Questionnaire (VRSQ) [11], administered in English language and pen-and-paper format.

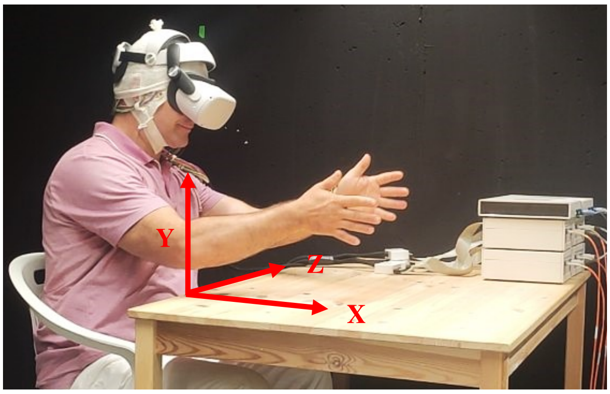

Figure 2: The experimental setup with Meta Quest 2 placed over the EEG cap. The axes represent the coordinate frame of recorded movement trajectories.

EEG measurement: We recorded the EEG signals with 64 gel-based passive EEG electrodes following the standard 10-20 system, with the ground and reference electrodes set at AFz and FCz, respectively. We kept the impedances below 10-15 kΩ. The EEG signals were recorded at 1 kHz using the NeurOne™ Tesla[4] EEG system. The amplifiers were powered by 7V batteries and connected to the main unit by fiber optic cables.

Data recording: For the integrated recording of the EEG and REVIRE data streams, we used the Lab Streaming Layer (LSL)[5] and its default recording program Lab Recorder. The REVIRE output included the position coordinates of both hands and a stream of event markers. The synchronized data streams were saved into a single XDF file. A Python[6] script was developed to convert the XDF files into FIF files that are compatible with the MNE-Python[7] library, which we used for EEG signal processing. EEG signals, event markers, and hand position data were combined into a mne.io.Raw object containing 64 EEG channels, one STIM channel with event markers, and six channels for right and left hand positions (XYZ coordinates for each hand).

Virtual Reality Sickness Questionnaire (VRSQ): As a measure of cybersickness, we used the VRSQ [11], which comprises nine symptoms rated on a 4-point Likert scale ranging from 0 - *Not at all* to 3 - *Severely*. The items are divided into *Oculomotor* and *Disorientation* categories. To calculate scores for each category, corresponding items are averaged and scaled to a 100-point maximum, and the average of both categories represents the total score.

Task performance: As a measure of performance, we computed trial completion times based on *trial start* and *trial end* event markers. In twelve trials, completion times could not be determined due to missing markers, leaving a total of 1,908 trials (636 ± 2.5 per task).

Movement trajectories: To align and analyze the EEG data based on the movement events, we determined the movement onsets from the hand position data. We focused this preliminary analysis on the reaching movements in *Drinking* and *Pouring* tasks where users began trials by grabbing the bottle and/or glass. The *Box* task was excluded due to variability in the starting position of the box. We identified reach onsets based on peaks in velocity, which we confirmed manually by visually inspecting the movement trajectories. We included 1,023 trials, corresponding to 80% of *Drinking* and *Pouring* trials, where the onset was clearly identifiable and the resting period exceeded 2 seconds.

EEG preprocessing: We used the MNE-Python library and its built-in functions to preprocess and analyze the EEG data. We cropped the raw EEG signals to include only the *Drinking* and *Pouring* task trials. We filtered the data with a notch filter at 50 Hz and then bandpass filtered the signals at 1-49 Hz. After visually inspecting the time series of the filtered signals, we removed and interpolated channels with consistent noise (1.1 ± 0.4 per recording). We then re-referenced the signals to a common average reference. We corrected blink, eye movement, muscle, and electrode noise artifacts through manual inspection of the ICA components. Due to substantial noise contamination from muscle activity and pressure of the HMD on electrodes, we took a selective approach, retaining 16.6 ± 3.2 or 26% of the components per recording. We segmented the cleaned data into epochs extending from -2 to 5 seconds around reach onset events. A total of 1,023 epochs (511.5 ± 0.5 per task) were included in the analysis.

Event-related spectral activity: Our preliminary EEG analysis focused on sensorimotor activity in alpha and beta frequency bands, which have been associated with motor learning, e.g., [12, 13], and are commonly used as features in EEG-BCIs [14]. We used the Morlet wavelet method to obtain time-frequency representations for the alpha (8-12 Hz) and beta (13-30 Hz) bands at a frequency resolution of 1 Hz and with the number of cycles in the wavelet at half the length of the frequency range. We summed the spectral power over the frequencies within each band and computed event-related spectral perturbation (ERSP) values by dividing time-frequency representations with the mean of the baseline period, followed by a logarithmic transformation. Focusing on motor activity, we considered the mean of ten channels at the bilateral primary motor cortex (C1, C3, C5, FC3, CP3, C2, C4,

[4] https://www.bittium.com/medical/bittium-neurone
[5] https://github.com/sccn/labstreaminglayer
[6] https://www.python.org/
[7] https://mne.tools/stable/index.html

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C6, FC4, and CP4). We plotted the EEG response against the movement trajectories (see Fig. 5) and estimated 0 to 3 seconds after the movement onset as the relevant time window for the reaching movement.

Statistical analysis: To assess the effects of practice and task type on completion times and EEG response, we opted for mixed linear models (MixedLM). The models were formulated with either 'Completion time', 'mu ERSP', or 'beta ERSP' as the dependent variable, 'Session' and 'Task' as fixed effects, and 'Participant' as a random effect. The dependent variables were aggregated across trials within a condition to obtain one value per task for every participant in every session. To evaluate whether REVIRE induced adverse symptoms, we compared the total VRSQ scores against a baseline of 25 (corresponding to the response 1 - *Slightly*, indicating mild symptoms) using a one-tailed t-test. We hypothesized that the scores would fall below this threshold.

RESULTS

Task performance: Over the course of the practice sessions, participants consistently reduced the time it took them to complete the task. This trend is evident both individually and after averaging across participants, as illustrated in Fig. 3, which shows completion times aggregated across tasks. The results of the MixedLM are detailed in Table 1. The analysis revealed a significant decrease in completion times from Session 1 to 4, and a significant difference between all tasks, but no significant interaction between the two factors.

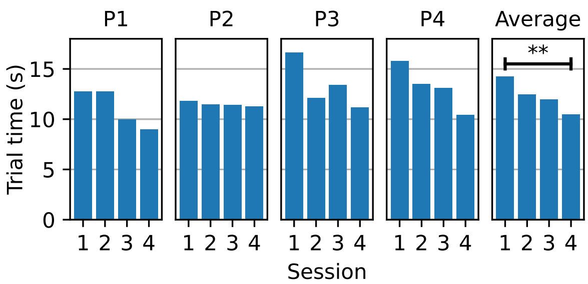

Figure 3: Mean completion times across practice sessions, averaged over tasks. Plotted for all four participants (P1 to P4), and participant average. $**p < 0.01$

Event-related spectral activity: EEG analysis showed a consistent increase in mu and beta ERSP across sessions, suggesting decreased involvement of sensorimotor areas as participants increased their proficiency. Figure 4 illustrates this trend for individual participants and the participant average, with ERSP aggregated across tasks. The results of the MixedLM are detailed in Table 2. The increase in ERSP values for both mu and beta was significant in Session 4 compared to Session 1. No significant effects of task condition or task-by-game interaction were found for either beta or mu ERSP, suggesting the influence of temporal dynamics rather than task-specific factors on EEG modulation. Fig. 5 illustrates the

Table 1: Mixed Linear Model Results for Completion Time

Effect	Estimate	*SE*	*p*
Intercept (S1, T1 vs. 0)	18.54	1.19	< .001
S2 vs. S1	-2.01	1.55	.20
S3 vs. S1	-2.07	1.55	.18
S4 vs. S1	-4.30	1.55	**.01**
T2 vs. T1	-3.12	1.55	**.04**
T3 vs T1	-9.83	1.55	**< .001**
S2×T2	0.45	2.19	.84
S3×T2	-0.73	2.19	.74
S4×T2	-0.67	2.19	.76
S2×T3	0.21	2.19	.93
S3×T3	0.18	2.19	.94
S4×T3	2.11	2.19	.34

Note: The participant variance is 0.87. S is session, T1-3 are Pouring, Drinking, and Box tasks. SE is the standard error of the estimate. Statistical significance was set at $p < .05$.

EEG response to the bimanual reaching movements in the *Pouring* task. A characteristic desynchronization of the sensorimotor rhythms was observed at movement onset. The magnitude of the response consistently decreased as the training sessions progressed. Diversification of ERSP levels across sessions was particularly pronounced during the first two seconds of the reaching movement. Alongside changes in motor activity, topographical plots showed a decrease in frontal activity across the sessions, suggesting reduced involvement of attentional and executive processes [13].

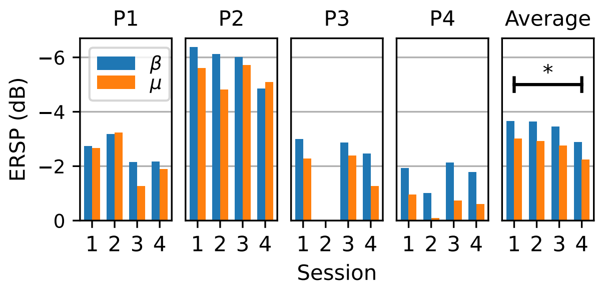

Figure 4: Motor beta and mu ERSP across practice sessions, averaged over tasks. Plotted for all participants (P1 to P4), and participant average. $*p < 0.05$. *Note:* Missing ERSP values for P3 in session 2 due to a technical issue.

Cybersickness: The descriptive statistics for VRSQ are detailed in Table 3. We found REVIRE to be well tolerated, with minimal cybersickness symptoms reported by all participants. Specifically, total VRSQ scores (8.91 ± 7.64) were significantly below the mild symptom threshold of 25, $t(3) = -18.26$, $p < .001$. Fig. 6 depicts the cybersickness ratings of all participants, which consistently fell in the range of no to negligible symptoms.

DISCUSSION

This paper introduced REVIRE, an immersive VR platform for BCI-based motor rehabilitation. We presented the results of a proof-of-concept study in which we tested

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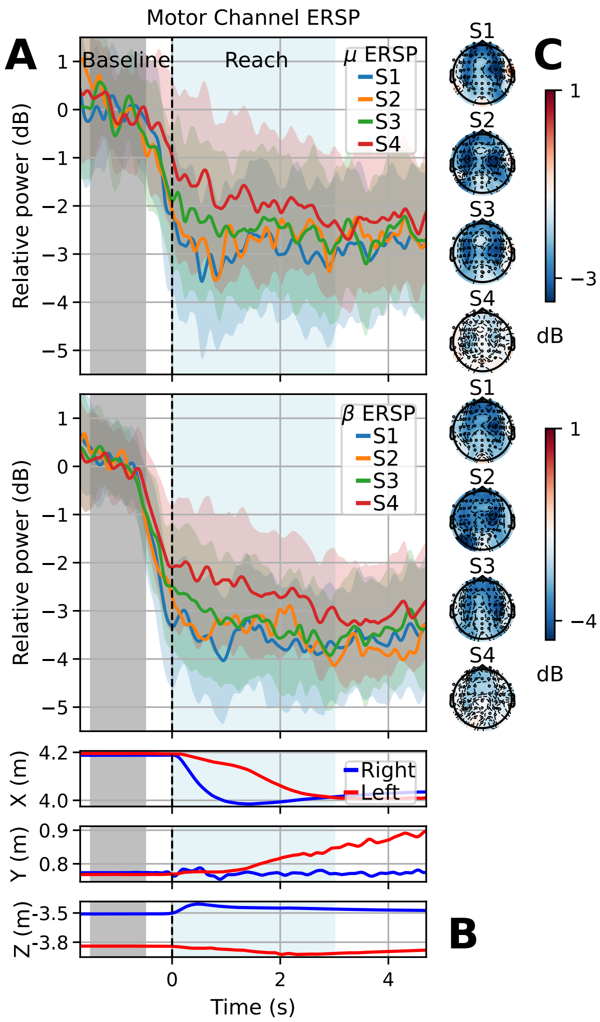

Figure 5: Grand-average of EEG responses and corresponding hand trajectories in the Pouring task. A: Within-epoch progression of mu and beta ERSP at motor channels. B: Left- and right-hand trajectories of the bimanual reaching motion on XYZ axes. C: Alpha (top) and beta (bottom) topographies of mean ERSP of the reaching movement duration (0-3s). S is session.

our VR-EEG setup on four healthy participants.

Task performance: Our results showed significant effects of training on participants' task performance across sessions, indicated by reduced trial completion times. We observed this trend not only in aggregated data but also at the participant level, demonstrating that completion times may provide an indicator for monitoring the progress of individual patients. Completion times in VR games have been found to correlate with clinical assessments [7, 15], supporting the potential of VR performance metrics as a meaningful assessment of rehabilitation progress.

Hand trajectories: REVIRE supports full hand tracking and stores hand movement trajectories. We have shown that the trajectories can be used to determine the precise movement onset or to identify specific actions, such as reaching movements. This can be a useful tool for analyzing EEG data recorded during natural self-paced movements. In addition, hand movement trajectories

Table 2: Mixed Linear Model Results for Mu and Beta ERSP

Effect	Estimate	*SE*	*p*
Mu			
Intercept (S1, T1 vs. 0)	-3.17	1.05	< .001
S2 vs. S1	0.44	0.59	.46
S3 vs. S1	0.64	0.54	.23
S4 vs. S1	1.23	0.54	**.02**
T2 vs. T1	0.02	0.54	.97
S2×T2	-0.20	0.83	.81
S3×T2	-0.48	0.76	.53
S4×T2	-1.04	0.76	.18
Beta			
Intercept (S1, T1 vs. 0)	-3.65	0.95	< .001
S2 vs. S1	0.28	0.59	.64
S3 vs. S1	0.30	0.54	.58
S4 vs. S1	1.09	0.54	**.04**
T2 vs. T1	-0.11	0.54	.84
S2×T2	-0.12	0.82	.89
S3×T2	-0.20	0.76	.79
S4×T2	-0.67	0.76	.38

Note: The participant variance is 3.84 for mu and 3.05 for beta. S is session, T1-2 are Pouring and Drinking tasks. SE is the standard error of the estimate. Statistical significance was set at $p < .05$.

Table 3: Descriptive Statistics of VRSQ Scales Across Sessions

Variable	Mean	Mdn	St. Dev.	IQR
Oculomotor	11.98	8.33	12.16	16.67
Disorientation	5.83	6.67	5.90	13.33
Total	8.91	9.58	7.64	11.04

have applications beyond what has been demonstrated in this preliminary analysis. By providing a direct quantitative measure of movement quality, clinicians can use trajectories to assess patient progress and highlight specific areas that may need improvement, such as range of motion, speed, or accuracy of movements.

Event-related spectral activity: Our study demonstrated the feasibility of capturing meaningful neural signals amidst considerable movement and the placement of a VR-HMD over EEG electrodes. Specifically, we observed a significant practice-related decrease in mu and beta ERSP magnitude, which is consistent with previous research on motor learning-related spectral changes, e.g., [12]. Our findings support the potential of EEG features as markers of rehabilitation progress.

Cybersickness: Participants' feedback indicated minimal cybersickness symptoms, confirming that our setup is well tolerated by users and further underscoring the suitability of REVIRE for patient use.

Limitations and future work: The main limitation of our study is the small sample size, consisting of only healthy participants, which limits the statistical validity and generalizability of our findings. Nevertheless, we observed promising trends and demonstrated the capability of our setup to provide meaningful data.

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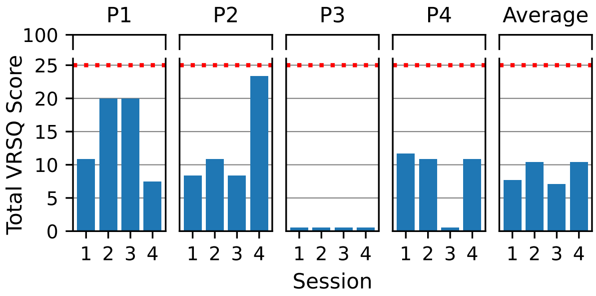

Figure 6: VR Sickness Questionnaire scores across sessions. Plotted separately for all four participants (P1 to P4), and for participant average. Scores below the red line indicate negligible to no cybersickness symptoms.

Our results demonstrated that REVIRE is well-suited for VR-BCI rehabilitation studies. Therefore, a future direction is to integrate the application into a closed-loop BCI system. By implementing real-time EEG processing and modifying the VR software to respond to neural signals, our application can provide neurofeedback or real-time customization of the training paradigm to the patient's neural state. Our results motivate further research to validate the application for clinical use and beyond, particularly with stroke patients and larger participant samples.

CONCLUSION

In this paper, we demonstrated the potential of REVIRE to provide an immersive, task-specific rehabilitation environment that yields comprehensive behavioral, hand motion, and EEG data for patient monitoring. We established the feasibility of our VR-EEG setup and its utility for further clinical research, offering a promising foundation for integrating VR and EEG in accessible BCI-based motor rehabilitation.

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