Employing Optical Brain Imaging for Real-Time Assessment of Brain Functions During Immersive Virtual Reality: Harnessing Potential for Neurorehabilitation

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***Abstract*—This ongoing study introduces a cutting-edge integration of immersive Virtual Reality (iVR) and functional Near-Infrared Spectroscopy (fNIRS) to facilitate real-time monitoring of brain activity during iVR-based tasks. By combining a High Tech Computer Corporation (HTC) Vive Pro VR headset with a multichannel fNIRS system, the platform provides a portable, non-invasive solution for investigating motor and cognitive control functions under immersive conditions. The study focuses on tasks that mimic real-world rehabilitation exercises, such as hand-grasping movements, designed to engage both motor and executive brain regions. Preliminary results from two healthy participants demonstrate robust hemodynamic responses in the Bilateral Motor Cortices (M1) and Dorso-Lateral Pre-Frontal Cortices (DLPFC) during iVR tasks, revealing increased neural activation compared to similar tasks performed in real-world and screen-based environments. Enhanced functional connectivity between the M1 and DLPFC was also observed, suggesting improved coordination of motor and cognitive processes. These findings highlight the potential of the iVR-fNIRS platform to capture unique patterns of brain engagement and functional activation during immersive virtual tasks. This novel approach addresses a critical gap in neurorehabilitation research by enabling continuous, real-time assessment of brain activity during therapy. The platform's portability and resilience to motion make it well-suited for clinical applications, including personalized rehabilitation programs for patients with neurological conditions. Future work will extend the study to larger populations and incorporate additional cognitive tasks to validate the platform's versatility and reliability. This research paves the way for innovative neuroscience tools and therapeutic interventions driven by Artificial Intelligence (AI), enhancing our ability to monitor and optimize brain function in immersive virtual environments.**

Keywords-Immersive Virtual Reality (iVR); Functional Near-Infrared Spectroscopy (fNIRS); Neurorehabilitation; Hemodynamic Response.

I. Introduction

Immersive Virtual Reality (iVR) has been increasingly recognized as a promising tool in neuroscience research and therapeutic interventions for neurological disorders [1]. By integrating various visual, auditory, and haptic stimuli, iVR creates an engaging and interactive virtual environment that simulates real-world interactions. This offers an unprecedented opportunity for cognitive and physical function training for many neurological applications, including neurorehabilitation, which aims to promote neuroplasticity through active training. However, current iVR-based methods are constrained by the lack of an effective method to monitor brain activity during iVR. Most studies rely on a pre- vs. post-training paradigm, where the effectiveness of the therapy is assessed after the completion of one or several therapy sessions by comparing the post-intervention brain functions to the baseline.

To address this limitation, our ongoing research explores the feasibility of combining iVR with a flexible, non-invasive optical brain imaging method to monitor the brain responses to iVR-based tasks in real-time. Specifically, we will utilize functional Near-Infrared Spectroscopy (fNIRS), which employs near-infrared light to measure the cortical hemodynamic/oxygenation activities. Sharing a similar neurological basis as functional Magnetic Resonance Imaging (fMRI), fNIRS provides unique advantages in its portability, relatively higher resilience to motion, and cost-effectiveness, making it particularly suitable for iVR applications [2].

In Section 2, we present the methods used to develop an integrated iVR-fNIRS platform, detailing the experimental setup and the procedures for monitoring brain activity during hand-grasping tasks in different environments. Section 3 outlines the results of our preliminary analysis, including signal quality, brain activation patterns, and functional connectivity during different experimental conditions. In Section 4, we discuss the implications of our findings, highlighting the potential of iVR-based neurorehabilitation and the need for further investigation. Finally, Section 5 concludes the paper by summarizing the research and proposing future work, including the integration of haptic feedback into the iVR-fNIRS platform for enhanced therapeutic outcomes.

II. METHODS

We developed an integrated iVR-fNIRS platform capable of reliably measuring brain oxygenation changes during iVR (Figure 1). The platform combines an HTC Vive Pro VR headset (HTC Corp., New Taipei, Taiwan) with a multichannel fNIRS system (Rogue Research Inc., Montreal, Canada), allowing us to monitor brain activity during immersive virtual tasks. To test the platform, we designed an iVR-based training task centered on hand grasping, a commonly used activity in upper extremity rehabilitation due to its role in improving motor and executive control functions [3].

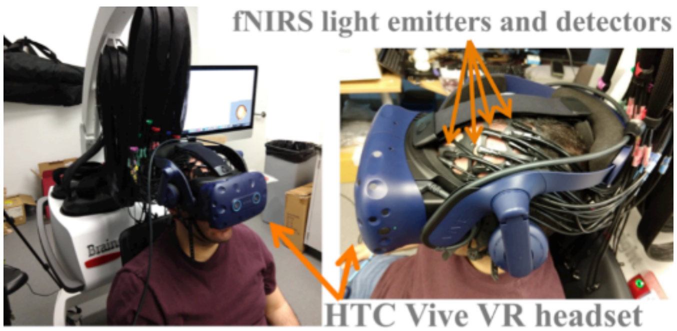

Figure 1: Test setup with commercial VR headset and multichannel fNIRS for real-time assessment of brain condition during VR.

We plan to recruit 30 healthy volunteers to participate in this study. For each participant, three data acquisition sessions will be conducted, with the same tasks presented (1) in the real-world environment, (2) in a non-immersive environment (computer screen), and (3) in the fully immersive VR environment (Figure 2). The order of sessions will be randomized to ensure the accuracy and reliability of the test. The same task will be performed 8 times within one session, while fNIRS will be used to continuously measure the brain responses to the hand-grasping task from the Bilateral Motor Cortices (M1) and the Dorso-Lateral Pre-Frontal Cortices (DLPFC).

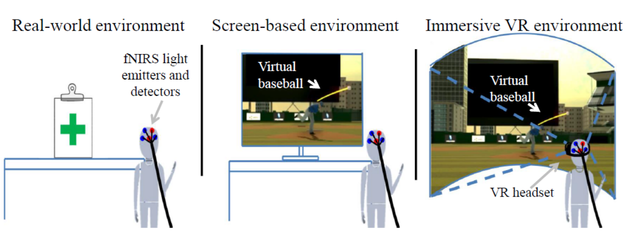

Figure 2: Hand grasping task in three environments: A real-world environment, a non-immersive VR environment, and an Immersive VR environment.

Participants will be invited to sit comfortably in a chair. (1) In the real-world environment session, a clipboard will be installed in front of them, displaying green or red cross indicators to signal the start or stop of tasks, respectively. The data acquisition session will last approximately six minutes, and involves 8 tasks of motor execution, where participants lift their right forearm and open and close their right hand according to the green or red indicator to mimic a baseball-catching motion. (2) In the computer screen environment, they will sit on a chair while a virtual baseball player avatar is displayed on a screen in front of them. The same data acquisition session will take place, where they will execute the ball-catching actions in response to the avatar's virtual baseball throws. (3) In the fully immersive VR environment (Figure 3), a VR headset will be installed on the participant's head together with the fNIRS light emitters and detectors, which will simulate a VR baseball field and a virtual player throwing a baseball at them (Figure 3). The same motor execution tasks will be performed, where they will open and close their right hand to complete the ball-catching actions in response to the virtual baseball being thrown at them. The VR game was developed using the Unity engine (Unity Technologies, San Francisco, United States).

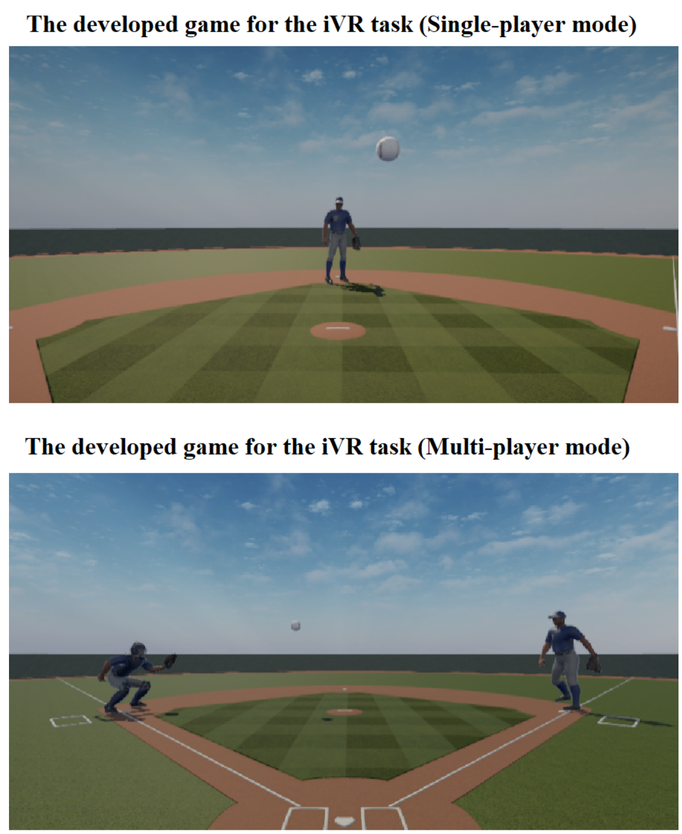

Figure 3: Hand grasping task in immersive VR environments: the single-player mode (interactive) and the multi-player mode (observatory).

A total of 10 fNIRS light emitters and 24 light detectors will be used in this study, forming 36 normal channels of 3cm to sample signals from the M1 and the DLPFC of both hemispheres (Figure 4). Six short-distance detectors will also be placed at approximately 1cm from the nearest light emitter to provide an estimation of the extracerebral signal components, such as the interferences from heart rate or blood pressure changes. fNIRS data will be sampled at 25Hz. In Figure 4, red and blue dots indicate light emitters and light detectors, respectively. Black dots represent the short-distance detectors. Yellow lines show the location of the formed fNIRS channels.

fNIRS data will be processed using the open-source Matlab toolbox Homer2 [4]. Briefly, the optical intensity time course will be converted to optical density changes. Band-pass filtering will be performed to limit the frequency range from 0.01Hz to 0.5Hz, removing components that are unlikely to have a neurological basis. The filtered optical density changes will be transformed into oxy-hemoglobin (HbO) and de-oxy hemoglobin (HbR) concentration changes using the modified Beer-Lambert law. The Hemodynamic Response Function (HRF) to the hand-grasping task in different environments will be estimated through the use of a general linear model, which will include short-distance fNIRS measurements to remove the physiological interferences.

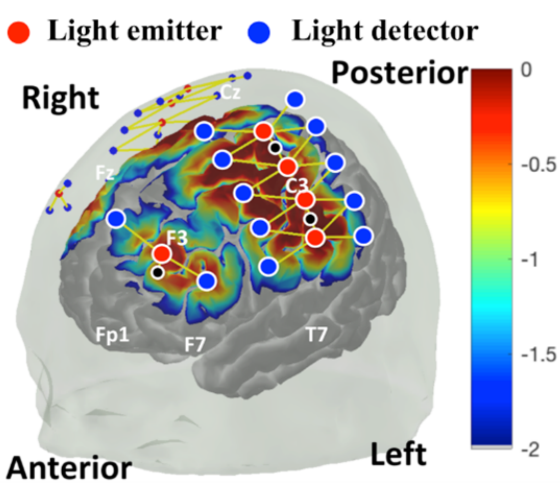

Figure 4: Depiction of the fNIRS channel setup used in this study.

We will also use beta-series correlation methods [5] to examine differences in the functional connectivity within and between the M1 and DLPFC to evaluate the impact of iVR on brain network functions [6].

III. Results

To date, we have collected and analyzed data from two healthy volunteers (one female). Preliminary results showed no significant signal interference between the two devices and high signal-to-noise ratios (~32 ± 13 dB) in fNIRS recordings during the iVR sessions. These results suggest that the fNIRS system provided reliable and accurate data under immersive VR conditions. In all the environments, fNIRS revealed HbO increases and HbR decreases in the bilateral M1 and DLPFC cortices during hand-grasping tasks (Figure 5).

Comparing iVR-based tasks with the real-world and the screen-based tasks, we observed higher levels of HbO increase and lower HbR response, indicating greater neural activation during iVR compared to both the real-world environment and the computer screen-based non-immersive environment (Table 1). These findings highlight potentially enhanced neural engagement and functional activation that occur during immersive virtual tasks.

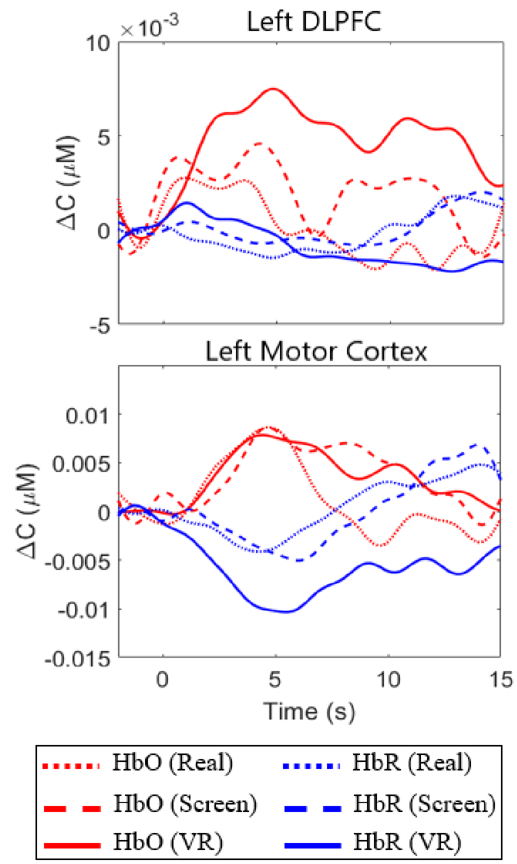

Figure 5: The HRFs of HbO and HbR concentration changes to motor tasks. Top: Left DLPFC; Bottom: Left M1. Overall, fNIRS revealed the highest levels of brain activities during iVR.

TABLE I: QUANTITATIVE COMPARISON BETWEEN HBO AND HBR LEVEL IN DIFFERENT ENVIRONMENTS. HBO AND HBR LEVELS WERE MEASURED IN BOTH DLPFC AND MOTOR CORTEX.

	Average HbO (μM)	Min HbO (μM)	Max HbO (μM)
DLPFC - iVR	0.0044551	-0.00044723	0.0074947
DLPFC - Screen	0.0018198	-0.0014499	0.0045801
DLPFC - Real	0.0011403	-0.0010942	0.0037368
Motor Cortex - iVR	0.0060339	-0.00039013	0.012586
Motor Cortex - Screen	0.004392	-0.00080191	0.010561
Motor Cortex - Real	0.0038074	-0.0010547	0.012893

	Average HbR (μM)	Min HbR (μM)	Max HbR (μM)
DLPFC - iVR	-0.00076602	-0.0022027	0.001435
DLPFC - Screen	-0.000083154	-0.00082238	0.0020052
DLPFC - Real	-0.00097372	-0.0023726	0.0002035
Motor Cortex - iVR	-0.00053821	-0.01034	0.00054269
Motor Cortex - Screen	-0.0059486	-0.0054591	0.0064086
Motor Cortex - Real	-0.0019377	-0.0065365	0.00020121

In addition to the HRF analyses, we estimated the functional connectivity between each pair of fNIRS channels, and observed more co-functioning brain areas and stronger remote network connections, especially between M1 and DLPFC, which are both key regions in the executive control network, during tasks executed in the fully immersive VR environment (Figure 6).

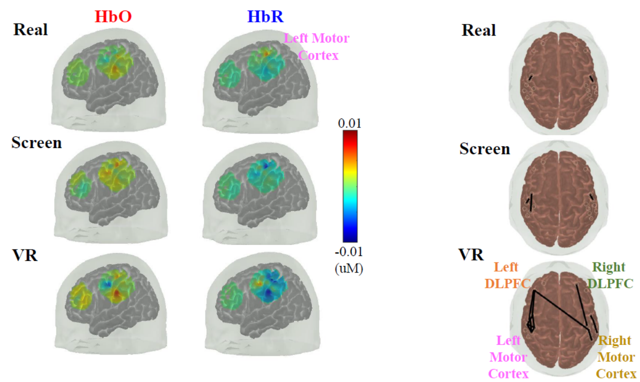

Figure 6: Connectivity analysis showed more connected brain areas during iVR task than the other environments, $p<0.05$, false discovery rate-corrected.

These results imply greater engagement of motor and cognitive control functions during iVR-based tasks.

IV. Discussion

The integration of iVR and fNIRS presents exciting opportunities for advancing neuroscience research and clinical applications. In this study, we developed an iVR-fNIRS platform that ensures optimized hardware compatibility and real-time data transmission. Preliminary findings demonstrate the potential of this combined platform in investigating motor and cognitive control functions during iVR-based tasks.

It is important to note that none of the experimental conditions (real-world, non-immersive VR, or immersive VR) incorporated tactile sensory feedback, such as interacting with a real ball. This decision aligns with the primary aim of our research: to design a neurorehabilitation approach that is accessible for diverse environments, beyond traditional hospital or rehabilitation center settings. Despite the absence of haptic feedback, our results suggest that iVR-based neurorehabilitation can potentially enhance brain activity and connectivity—a critical goal in neurorehabilitation aimed at fostering more effective and efficient brain stimulation.

Furthermore, the findings indicate that the iVR environment may offer a greater rehabilitative effect compared to real-world or non-immersive VR settings. This underscores the potential value of iVR as a platform for neurorehabilitation and warrants further investigation into its applications. Looking ahead, we plan to incorporate haptic feedback into the platform and examine its influence on the outcomes of our experiments. By doing so, we aim to explore whether the addition of tactile sensory input further enhances the rehabilitative effects observed in the iVR environment.

V. Conclusion and Future work

Combining iVR and fNIRS provides an effective method to evaluate brain activity and function in a fully-immersive virtual environment. In this ongoing study, our preliminary data showed higher levels of brain activation and connections during iVR-based tasks compared with real-world environment, or computer screen-based non-immersive environment. With the integration of AI into the iVR-fNIRS platform, we offer significant potential to enhance the personalization and effectiveness of rehabilitation programs. AI-driven algorithms can be used to analyze large datasets of brain activity in real-time, leading to identifying patterns in neural responses that may not be immediately apparent to human researchers. For instance, machine learning models could be trained on brain activity data collected during iVR-based tasks, enabling the platform to adaptively modify the difficulty and nature of rehabilitation exercises based on individual performance and neural engagement. Furthermore, AI could facilitate the creation of personalized rehabilitation protocols by predicting optimal tasks or interventions tailored to each participant's cognitive and motor abilities, thus improving rehabilitation outcomes. By integrating these AI-driven models, the platform could offer dynamic and adaptive therapeutic programs that evolve with the patient's progress, making neurorehabilitation more efficient and targeted. As data collection continues, this research has the potential to lay the groundwork for innovative tools in neuroscience and neurorehabilitation, including facilitating immediate evaluation of iVR-based training efficacy and enabling the development of advanced, AI-driven personalized rehabilitation programs for both physical and cognitive recovery.

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 ISBN: 978-1-68558-266-1