Observing Actions Through Immersive Virtual Reality Enhances Motor Imagery Training

Jin Woo Choi, Byung Hyung Kim, Sejoon Huh, and Sungho Jo

Abstract—Visual information plays an essential role in enhancing neural activity during mental practices. Previous research has shown that using different visual scenarios during mental practices that involve imagining the movement of a specific body part may result in differences in performance. Many of these scenarios utilize the concept of embodiment, or one’s observation of another entity to be a part of oneself, to improve practice quality of the imagined body movement. We therefore hypothesized that applying immersive virtual reality headsets, with their ability to provide rich immersion and illusion by presenting egocentrically simulated virtual scenarios, and action observation to motor imagery practice will result in significant improvement. To explore the possible synergy between immersive systems and motor imagery, we analyzed the electroencephalogram signals of our participants as they were presented the same virtual hand movement scenario with two different mediums: an immersive virtual reality headset and a monitor display. Our experimental results provide evidence that the immersive virtual reality headsets induced improved rhythmic patterns with better discriminating spatial features from the brain compared to the monitor display. These findings suggest that the use of immersive virtual reality headsets, with the illusion and embodiment they provide, can effectively improve motor imagery training.

Index Terms—Virtual reality (VR), mental practice, motor imagery, action observation, embodiment, neural activity, electroencephalography (EEG), event-related desynchronization (ERD), machine learning.

I. INTRODUCTION

Patients who seek to improve their control over their motor functions during clinical treatment and rehabilitation commonly undergo motor imagery training, the mental practice of a motor task without execution in reality. Previous research has shown that merely thinking of movement still enhances neuroplasticity, helping patients recover motor functionality [1]–[3]. Motor imagery also plays a crucial role in the field of brain-computer interfaces, as it elicits event-related desynchronization (ERD), a decrease in oscillatory brain activity in the alpha (8–13 Hz) and beta (13–25 Hz) frequency bands [4]–[6]. Due to its various applications in multiple fields and potential to help patients, motor imagery has therefore been under the academic spotlight, with researchers looking for ways to improve the effectiveness of motor imagery.

One such way to enhance motor imagery is action observation, or the observation of the movement of a body part related to the motor imagery task [7]–[9]. Previous research has suggested that mirror neurons cause the activation of corresponding regions by going through action understanding and learning through imitation [10]. Action observation therefore serves as a stimulant for inducing mirror neurons when one observes another entity mirroring the imagined body movement [11]. One of the commonly used methods that utilize action observation is mirror therapy, where the observation of the reflection of a moving body part provides the illusion of its contralateral counterpart with limited motor function moving normally [12], [13]. Recent studies have shown that such visual guidance can enhance brain activity when used along with motor imagery, as both action observation and motor imagery are related to the activation of targeted brain regions [14]–[16]. As a result, many clinical trials utilize repeated action observation and motor imagery training to improve motor imagery performance [17]–[19].

Considering that action observation for motor imagery practice relies on presenting simulated environments different from the real world, the relationship between the performance of motor imagery and embodiment has also been recently investigated [20]–[23]. To provide a richer sense of embodiment, an identification of an artificial body and its simulated movement as if it were one’s own, various protocols were utilized along with motor imagery tasks. For instance, Sollfrank et al. [24] presented 5 different types of movement in both 2D and 3D using a stereoscopic monitor and glasses, while encouraging the participants to take ownership of the presented body. The results showed that significant differences in the ERD patterns between 2D and 3D movements were observed, with an enhanced ERD for the 3D visualization group. Another example from Nagai et al. [25] investigated ERD ratios while the participants observed an open-clench hand movement of their own hand, the movement of another person’s hand, and no movement through the tablet monitor while performing motor imagery. The results indicated that observing the participants’ own hands showed the strongest ERD ratio compared to the other given conditions. Such studies revealed that richer visualization and stronger ownership of the observed movement leads to better ERD occurrences.

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As one of the recently developed visualization technologies, immersive virtual reality (VR) headsets have been used to amplify body ownership [26]–[29]. As devices used to display and implement virtual reality, VR headsets provide full immersion by blocking the view of the real world and being egocentrically stabilized toward the direction the user is facing [30], [31]. Furthermore, presenting scenarios graphically through VR headsets blurs the line between the virtual world and the real world, enabling users to perceive the illusion that what they see is real. With the aforementioned advantage, VR headsets were often utilized for action observation during motor imagery practice [32]. For instance, Vourvopoulos et al. [33], [34] developed a VR based neurofeedback system to help patients with enhancing their motor imagery performance for tasks such as arm or limb movements. Such systems visualize a graphical body movement in response to the participant's brain activity, serving as feedback for the motor imagery.

In this study, we focused on whether rich immersion from VR may influence repeated motor imagery practice with action observation of hand grasping movements. To investigate whether the difference in display medium influences action observation while performing motor imagery, we displayed the same graphical hand grasping movements through two different displays: an immersive VR headset and a monitor display. Furthermore, unlike previous research in which the presented scenario was mainly used as feedback, our study used our graphical scenario as a stimulus to put more emphasis on the effects of illusion and embodiment from immersive VR on action observation during motor imagery training. To examine brain activities while using the two distinctive media, we utilized electroencephalography (EEG) and identified changes in the elicited neural signals of the sensorimotor cortex. To measure the discriminability of spatial brain activity patterns during different motor imagery tasks, we applied machine learning techniques, a commonly used method in brain-computer interfaces to learn and discriminate brain activities from different types of motor imagery.

II. PROCEDURES

We performed two experiments on each participant to investigate whether using an immersive VR headset to provide action observation during motor imagery practice has an effect on performance:

- Immersive VR-based motor imagery (IVR-MI): an experiment that utilized the immersive VR headset to provide graphical hand grasping scenarios for motor imagery practice
- Monitor display-based motor imagery (MD-MI): an experiment that used the non-immersive monitor display for displaying the same scenarios during motor imagery practice

To analyze the influences of VR on motor imagery, the MD-MI results were used as the control.

A. Participants

A total of 20 healthy participants between the ages of 20 and 37 were recruited for the two experiments. None of the participants had any neurological diseases or other issues that would hinder motor imagery performance. Prior to the experiments, all participants were also required to use the VR headset for an extended period of time to ensure they did not have any issue with using the VR headset.

Participants were randomly assigned into two groups of equal numbers: group A performed MD-MI prior to IVR-MI, and group B performed IVR-MI prior to MD-MI. To lessen the possibility of the former experiment influencing performance of the latter experiment, the latter experiment was held at least 7 days after the former experiment. Experiment results were also not revealed to the participants until the end of the two experiments to avoid providing any feedback that may influence performance.

The data collected from each participant was visually inspected, and data from two of the participants were excluded in our analysis as they exhibited extensive noise, leaving a final total of 18 participants for analysis. The number of participants remained equally distributed to the two assigned groups.

All participants gave their written consent after they were given detailed information on the experimental procedures. This study was approved by the Korea Advanced Institute of Science and Technology Institutional Review Board.

B. Protocols

The graphical scenario, which consists of two virtual hands and arrows on a dark background, was implemented with the
Unity game engine (Unity Technologies, San Francisco, CA, USA). Prior to each experiment, the positions of the virtual hands were adjusted such that the distance between the two virtual hands approximately equaled the shoulder-width of the participant (Fig. 1a).

1) IVR-MI Settings: After wearing the EEG cap with electrodes, participants wore an Oculus Go (Oculus VR, Menlo Park, CA, USA) with the vertical strap unused in order to prevent the strap tightening over the overlapped electrodes.

2) MD-MI Settings: In MD-MI, a display monitor with a monitor arm that provided three degrees of freedom was placed on the desk in front of the participant. Each participant was allowed to freely adjust the angles of the monitor arm. Each participant was permitted to adjust the camera view angle within the Unity application to maximize the ownership of the virtual hands. Participants were asked to place their hands on the desk such that their own hands were overlapped by the virtual hands.

C. Data Recording
BrainProducts’ actiChamp and actiCAP (BrainProducts, Munich, Germany) were used to retrieve EEG data from the scalp of each participant. The data was sampled with a sample rate of 500 Hz, and the active electrodes were placed according to the international 10-20 system. The EEG signals from 20 electrodes (FC5, C5, CP5, FC3, C3, CP3, FC1, C1, CP1, Cz, CPz, FC2, C2, CP2, FC4, C4, CP4, FC6, C6, CP6) placed around the sensorimotor cortex were recorded throughout the experiments, with ground and reference electrodes located at positions AFz and Fz, respectively (Fig. 1b). The EEG signals were recorded using BrainVision, and the impedance from each electrode was kept under 5 kΩ to obtain high-quality data. The data was band-pass filtered between frequencies of 8 and 25 Hz. After collection, the EEG data was then re-referenced by applying the average reference over all of the used electrode positions. The resulting preprocessed data was used for the analysis of neural activities.

D. Experimental Design
The experiments were held in a dark, soundproof room to minimize any environmental distractions. Each motor imagery experiment consisted of six sessions of ten consecutive motor imagery trials. Participants were permitted to rest between sessions if needed. Each trial was composed of a randomized sequence containing one continuous right hand grasping imagery task, one continuous left hand grasping imagery task, and one resting task (Fig. 2a).

A single trial consisted of an initial 4-second instruction period and a subsequent 6-second motor imagery period followed by a 2-second resting period (Fig. 2b). During the instruction period, participants were given a cross cue indicating a resting task, or an arrow cue indicating a left or right hand grasping imagery task, to inform participants on what the next task is and instruct them to gaze at the corresponding hand. Throughout the entire motor imagery period immediately after the instruction period, the virtual hand corresponding to the arrow cue simulated a sequence of grasping movements, and the participants were instructed to observe and imagine performing the same movement kinesthetically [35]. Lastly, during the resting period, the virtual hands remained motionless and participants were permitted to move or blink their eyes in order to prevent eye fatigue. For both the instruction period and the motor imagery period, subjects were instructed to avoid any movements including eye blinking. Both virtual hands were shown throughout the entire experiment, and the participants were expected to imagine them to be their own hands.

III. METHODS

A. ERD Analysis
As previous studies have shown that the brain regions corresponding to the electrode positions C3 and C4 are correlated with the right and left hand grasping movements, respectively, the data from these two positions were analyzed to evaluate ERD performance [36]. To measure changes in brain activity from a single session, we first computed the mean power spectrum of the recorded EEG data from the three motor imagery tasks with the following equation:

$$PSD_{s,task}(f, t) = \frac{1}{n} \sum_{r=1}^{n} P_{r,task}(f, t)$$

where $s$ is a specific session, $task$ is a task indicating left or right motor imagery ($m$) or resting imagery ($r$), $f$ is a
frequency band, $t$ is a specific time interval, $tr$ is a specific trial of a session, $n$ is the number of trials, and $P_{tr, task}$ is the power spectrum of a trial of a chosen task.

To analyze the ERD amplitude of participants elicited from left and right grasping motor imagery of each session over time, we computed the ERD ratio of the two motor imagery tasks with respect to the resting task using the following equation:

$$ERD_{s,m}(f, t) = \frac{PSD_{s,r}(f, t) - PSD_{s,m}(f, t)}{PSD_{s,r}(f, t)} \times 100\%\quad(2)$$

The ERD ratio in each session is therefore calculated with the differences in the characteristics of the elicited brain patterns during different motor imagery tasks for each electrode position.

In order to analyze the motor imagery performance of each experiment, we further computed the average ERD ratio of participants in each experiment by applying the following equation:

$$ERD_{avg}(f, m) = \frac{1}{n} \frac{1}{t_e - t_s} \sum_{s=1}^{n} \sum_{t=t_s}^{t_e} ERD_{s,m}(f, t)\quad(3)$$

where $n$ is the number of sessions, and $t_s$ and $t_e$ are the start and end times of a motor imagery period. Considering that the most reactive frequency band may vary for each individual [37]–[39], the frequency band of each participant for the two equations was determined by selecting the frequency band of bandwidth 2 Hz that resulted in the maximum averaged ERD ratio of all the tasks from the two experiments.

The ERD results of C3 and C4 from right hand and left hand grasping motor imagery were analyzed separately to explore the performance of participants during two different tasks. To investigate the effects of using different display media on each participant, we applied two-way ANOVA on the computed average ERD values where the assigned group, indicating the order of the experiments, and the display medium are used as the two factors. To further examine statistical enhancements of ERD on each session for participants, we applied a Dunnett-type non-parametric multiple contrast test in which the ERD ratios from the first session was used as the control. Thus, the ERD ratios for right hand motor imagery and left hand motor imagery tasks were compared separately between the two experiments. (Fig. 3).

### B. Discrimination Analysis

Classical machine learning models were also constructed to further evaluate performance by analyzing discrimination of neural activity during the two experiments. In order to compare the classification accuracies for each participant in the two experiments, the 6-second EEG data from each motor imagery period was extracted. To enlarge the amount of data for the model to learn, we further applied data augmentation on each 6-second EEG data by splitting the data into 2-second-long time windows with a stride of 100 milliseconds.

The common spatial pattern (CSP) algorithm was applied to extract spatial features from the preprocessed EEG data [40], and Fisher’s linear discriminant analysis (LDA) was used to create classification models that predict whether a segment of EEG data refers to the resting, left or right hand motor imagery task [41]. To evaluate the motor imagery EEG data, we applied two different cross-validation methods: 1) a 6-fold cross-validation where the data from a single experiment is analyzed and each fold corresponds to the data retrieved from

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**Table I**

<table>
<thead>
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<th>Test type</th>
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<th>Normality</th>
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<td>[A, IVR]</td>
<td>[A, MD]</td>
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<td>ERD (C3)</td>
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</table>
Fig. 4. (a) The grand average ERD ratio of all participants from both MD-MI and IVR-MI. The error bar represents standard deviation of ERD ratio. ** p < 0.01, *** p < 0.001. (b) The grand average ERD amplitude plot of all participants. The shaded region represents standard deviation of ERD amplitude, and the gray lines on the x axis represents the time domain where p < 0.05.

IV. RESULTS

A. Verification of Assumptions for Statistical Analysis

Necessary assumptions were verified prior to parametric tests using ANOVA on the ERD results for left hand and right hand motor imagery as well as cross validation accuracy results. Table I shows the results for Shapiro-Wilk normality test and Levene’s homogeneity of variance test. The p-value results indicate that both normality and homogeneity of variance were not violated for all cases (p > 0.05).

B. Experiment-Wise Analysis of ERD Performance

To compare the performance of participants using the two different display media, we analyzed both the ERD ratios, represented by the average ERD ratio of participants during motor imagery periods, and the ERD amplitudes, representing the average of the ERD elicited over time gathered from each session.

The ERD ratio and ERD amplitudes for left hand and right hand motor imagery for the two experiments were compared as shown in Fig. 4. The ANOVA results in Fig. 4a showed that the ERD ratio from IVR-MI was larger compared to MD-MI for left hand motor imagery (49.32 ± 12.08 and 34.75 ± 14.75 for IVR-MI and MD-MI, respectively) with an extremely statistically significant difference ($F(1,16) = 20.182, p < 0.001$). IVR-MI also showed a larger ERD ratio for right hand motor imagery compared to MD-MI (53.29 ± 12.57 for IVR-MI).
and 41.32 ± 15.19 for MD-MI) with the difference being very significant ($F(1,16) = 14.693, p < 0.01$). On the other hand, no significant difference were shown between the two participant groups for both left hand and right hand motor imagery ($F(1,16) = 0.131, p > 0.72$ and $F(1,16) = 1.034, p > 0.32$, respectively).

Fig. 4b shows the ERD amplitude of participants with respect to time, which were computed by averaging the ERD amplitudes of each participant over all sessions. The red and blue amplitude plots from IVR-MI and MD-MI indicate that the ERD showed significant differences during the motor imagery periods from both left and right hand imagery, with greater ERD amplitudes from IVR-MI compared to MD-MI. As indicated by gray marks on the x-axis, a significant difference in the two amplitudes was observed between time domain ranges 1.0 to 5.4 seconds and 6.2 to 7.0 seconds for left hand motor imagery, and in time domain ranges 1.4 to 5.8 seconds and 6.0 to 7.2 seconds for right hand motor imagery. No statistical difference was shown during the instruction period ($t < 1.0$ s and $t < 1.4$ s for left hand and right hand motor imagery, respectively) and the end of the resting period ($t > 7.0$ s and $t > 7.2$ s for left hand and right hand motor imagery, respectively).

C. Experiment-Wise Cross-Validation

Fig. 5 shows 6-fold subject-dependent cross-validation accuracy results for IVR-MI and MD-MI, where a single fold represents the data acquired from each session. The ANOVA results showed that the difference in the accuracies of the two media were extremely significant ($F(1,16) = 20.990, p < 0.001$), with the accuracy for IVR-MI being higher than that for MD-MI ($67.85 ± 13.50$ for IVR-MI and $57.49 ± 13.96$ for MD-MI). Contrarily, the difference between the two groups showed no statistically significant difference ($F(1,16) = 0.008, p > 0.93$).

D. Session-Wise Changes in ERD Performance

We further analyzed how ERD performance for left hand and right hand motor imagery changes over sessions. As shown in Fig. 6, the ERD ratio showed a positive linear relationship over the sessions for both IVR-MI and MD-MI during left hand motor imagery ($r = 0.345, p < 0.001$ for IVR-MI and $r = 0.260, p < 0.01$ for MD-MI). Right hand motor imagery also showed similar results ($r = 0.362, p < 0.001$ for IVR-MI and $r = 0.181, p > 0.05$ for MD-MI). In both left hand and right hand motor imagery, the r-values and p-values were statistically stronger for IVR-MI compared to MD-MI.

<table>
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<tr>
<th>Left hand motor imagery ERD</th>
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<td>Experiment</td>
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<td>IVR-MI</td>
<td>Statistic</td>
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<td></td>
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<tr>
<td>MD-MI</td>
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The ERD ratio from the first session was chosen as a baseline and compared with ERD ratios of other sessions to analyze the improvements of ERD performances over sessions, as shown in Fig. 6 and Table II. For left hand motor imagery, participants during both IVR-MI and MD-MI showed significant improvements starting from session 5, but with stronger significance level for IVR-MI ($p < 0.01$ and $p < 0.05$ for IVR-MI and MD-MI on session 5, $p = 0.014$ and $p = 0.032$ for IVR-MI and MD-MI on session 6). For right hand motor imagery, participants were able to show significant differences in performance only when using the VR headset ($p < 0.05$ and $p < 0.01$ for sessions 4 and 6) while no significant improvements were observed throughout repeated sessions when using the monitor screen.

### E. Session-Wise Changes in Cross-Validation

The results of discriminating brain activity patterns using 10-fold cross-validation on each session where a single fold represents the data from each trial is shown in Fig. 7. For both IVR-MI and MD-MI, the accuracy results showed positive linear relationships ($r = 0.276$, $p < 0.01$ and $r = 0.136$, $p > 0.05$ for IVR-MI and MD-MI, respectively). The $r$-values and $p$-values for cross-validation accuracy over sessions were stronger for IVR-MI compared to MD-MI.

To analyze the improvements of cross-validation accuracy over sessions, we applied Dunnett-type non-parametric multiple contrast test on the accuracy results of the first session over remaining sessions. The results in Fig. 7 and Table III indicate that the participants during IVR-MI were able to show significant improvements in discrimination starting from session 5 ($p < 0.01$ and $p < 0.05$ for sessions 5 and 6, respectively), while no significant difference was observed during MD-MI.

### F. Topography Map of Fisher’s Ratios

To further investigate the spatial characteristics that were elicited from different hand imagery tasks, we applied Fisher’s ratio on each electrode using the ERD results [42]. As shown in Fig. 8, the electrode positions C3 and C4 were the major factors for distinguishing between left hand and right hand motor imagery. Fisher’s ratios on C3 and C4 were both stronger for IVR-MI (0.997 for C3 and 0.566 for C4) compared to the Fisher’s ratios of MD-MI (0.544 for C3 and 0.377 for C4).

### V. Discussion

In this study, the two experiments of using the VR headset and monitor display as mediums of observing left hand and right hand movements were held to investigate the impact of immersion and illusion on motor imagery practice. By comparing the ERD ratios and cross-validation accuracies obtained from the two experiments, we have provided evidence that perceiving the same action through different mediums may result in different motor imagery performances during practice.

The results from our study show that participants were able to obtain better motor imagery performance when using the VR headset. In terms of practicing motor imagery through repeated training, we have not only confirmed that repeating action observation influences motor imagery performance of participants as suggested in other studies [8], [43], but also found that using the VR headset may improve the performance of motor imagery with less time cost. Through our results of the ERD ratio and cross-validation accuracy both showing greater improvement using the VR headset, we have confirmed that using the VR headset is more effective at improving ERD performance and increasing spatial discrimination of brain activity compared to the monitor display.

We also investigated the ERD amplitudes and Fisher’s ratios to address concerns that merely having a different display medium influenced the ERD ratios from the central motor cortex (C3 and C4). The ERD amplitude patterns in our
results show a slight increase during the instruction period with no significant difference, followed by a statistically significant difference between the two experiments with a major increase during the motor imagery period, and then subsequently showing a decrease during the resting period (Fig. 4b). While we expect that the slight increase with no significant difference during the instruction period was the result of preparation and planning of the instructed movement [44, 45], a major increase with significantly greater ERD amplitudes for IVR-MI compared to MD-MI only during the motor imagery and early resting periods indicates that such statistical differences were elicited by motor imagery performance. Furthermore, Fig. 8 revealed that the major spatial characteristics that distinguish different motor imagery tasks were from the C3 and C4 electrodes for both experiments, indicating that merely a difference in display medium had little influence on factors that may affect our results such as spatial characteristics from the visual cortex [46]. These results indicate that action observation through the VR headset is more effective than the monitor display for motor imagery performance.

As previously mentioned, we focused on whether immersion and illusion through the VR system is effective for repeated motor imagery training with action observation. Our hypothesis was verified through ERD performance and the cross-validation results that showed a stronger ERD ratio and more discriminable spatial brain activity throughout repeated motor imagery practice. The major component of VR headsets that caused such enhancements on motor imagery performance is immersion, which has been reported to improve illusion and embodiment in previous studies [47]–[49]. While previous research was conducted to improve motor imagery performance with increased sense of embodiment by conducting experiments using different scenarios such as comparing gomino and armroom [21] or comparing between the absence and existence of anatomical congruence when using a monitor displaying a simulated hand [19], our results show that rich immersion itself influences motor imagery (by presenting the same graphical hand movement). Thus, using immersive VR headsets may prove beneficial to motor imagery training compared to non-immersive displays for any graphical scenario that can be simulated.

There are some limitations in and possible improvements to our study. With much research confirming that using different visual scenarios may result in different motor imagery performances [50], [51], there may be some concerns that the graphical scenarios of our study could also be considered to be different in some way, as the scales of the virtual hands may not exactly be the same for both display mediums. To overcome this issue, we focused on the feedback from each participant when adjusting the sizes to maximize embodiment before beginning each experiment. Additionally, although we adjusted various environmental components to greater embodiment in our study, we did not directly quantify each user’s levels of embodiment during the two experiments. As there existed a considerable gap in time between the two experiments, we deemed any possible survey or questionnaire to be potentially unreliable, and instead used the findings of previous work to claim embodiment was enhanced with VR. Lastly, our relatively small sample size is also a limitation. Although many repeated trials were conducted by each participant, the statistical power of our analysis may be limited considering the variation within the performances of each individual. Thus, the results in our study should be interpreted carefully. With the results of our research, a future study would focus on using our metrics to compare the use of the VR headset, a fully-immersive tool for visualization, and the use of stereoscopic 3D glasses, a semi-immersive virtual reality system that also showed enhanced motor imagery performance in a previous study [24], as their differences were often compared in other fields of study as well [52]–[54].

VI. CONCLUSION

Unlike previous research, which focused on comparing the visual scenarios themselves for action observation and motor imagery, we focused on the combined effect of immersive VR and embodiment on motor imagery. Inspired by the ability of VR headsets to provide more realistic experiences with enhanced illusion and immersion compared to other existing mediums, we investigated whether immersive VR headsets can also be used to enhance motor imagery performance by comparing a VR headset and a monitor display for action observation of the same virtual hand movements.

We have investigated two different aspects of brain patterns related to motor imagery performance of the two mediums: the change in the oscillatory rhythms of signals from the motor imagery-related brain regions, and the discriminability of the signals’ spatial characteristics, which was explored using a machine learning model commonly used for brain-computer interfaces. The results from the two analyses in our study showed that using the VR headset may result in greater oscillatory changes and spatial discrimination in the neural signals. Thus, we propose that using the VR headset, with the combined usage of immersion and illusion, can be better adopted for presenting action observation during motor imagery practice in the fields of clinical treatment, rehabilitation, and brain-computer interfaces.

REFERENCES


