# A Brain–Computer Interface-Based Action Observation Game That Enhances Mu Suppression

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***Abstract*— Action observation training based on the theory of activation of the mirror-neuron system has been used for the rehabilitation of patients with stroke. In this paper, we sought to assess whether a brain–computer interface (BCI)-based action observation rehabilitation game, using a flickering action video, could preferentially activate the mirror-neuron system. Feedback of stimulus observation, evoked by the flickering action video, was provided using steady state visually evoked potential and event-related desynchronization. Fifteen healthy subjects have experienced the game with BCI interaction (game and interaction), without BCI interaction (game without interaction), observed non-flickering stimuli, and flickering stimuli without the game background (stimuli only) in a counter-balanced order. The game and interface condition was resulted in significantly stronger activation of the mirror-neuron system than did the other three conditions. In addition, the amount of mirror-neuron system activation is gradually decreased in the game without interface, non-flickering stimuli, and stimuli only conditions in a time-dependent manner; however, in the game and interface condition, the amount of mirror-neuron system activation was maintained until the end of the training. Taken together, these data suggest that the proposed game paradigm, which integrates the action observation paradigm with BCI technology, could provide interactive responses for whether watching video clips can engage patients and enhance rehabilitation.**

***Index Terms*— Action observation, brain-computer interface, flickering exercise video, game, mu suppression, steady state visually evoked potential.**

## I. INTRODUCTION

PATIENTS with stroke experience motor function impairment resulting from neuronal injuries after stroke. The recovery of motor function largely depends on brain plasticity [1], [2]. Successful brain plasticity can be accomplished with early and intensive rehabilitation training because brain plasticity is most effective just after stroke [3].

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For patients who are too impaired to engage in traditional rehabilitation, the action observation paradigm, which evokes the mirror-neuron system (MNS), could be an alternative intervention [4], [5].

The MNS comprises a group of specialized neurons that "mirror" the activation of neurons involved in one's own actions and behavior, when visualizing others performing those actions [6], [7]. It has been hypothesized that the activation of the MNS could lead to functional enhancement. Studies have shown that motor imagery and action observation activate the MNS, which leads to the facilitation of brain plasticity and positive rehabilitation outcomes for patients following stroke [8]–[11]. As suggested in literature [12], [13], examining the power of mu band (8–13 Hz) oscillations in electroencephalography (EEG) is a convenient and non-invasive method to study human MNS function and the power of Mu rhythm attenuation during motor movement, action observation [14]–[16], or motor imagery [17].

Action observation is cost effective and advantageous because it can be applied without considerable technical skill. However, there may be shortcomings if patients are easily bored and do not engage in the training for the required length of time. In addition, it is difficult to pay attention for long periods, and attentive watching is an important component of the action observation paradigm. For effective action observation, stimuli that activate the MNS and engage patients must be considered.

Maintaining engagement in training is required to augment patient compliance and gain positive outcomes in rehabilitation training. The neurofeedback technique has been introduced to enhance or facilitate a specific brain function by providing feedback according to brain activation related to specific tasks or mental status and to help users augment their corresponding brain responses [18]–[21]. An important factor in rehabilitation using neurofeedback is to provide proper feedback, which is closely related to the user's intentions [22]. A successful closed loop with the proper feedback will capture one's attention and ensure training compliance for longer periods.

To apply the neurofeedback paradigm into action observation paradigms to augment MNS activations, measuring MNS activation with EEG, such as event-related desynchronization (ERD), could be used to detecting attention and

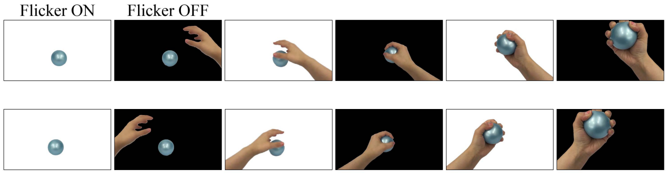
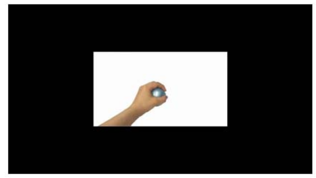
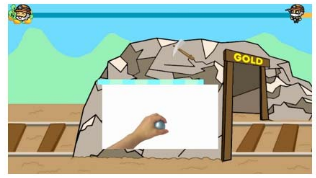



Fig. 1. Flickering action video showing the left or right hand picking up a ball.

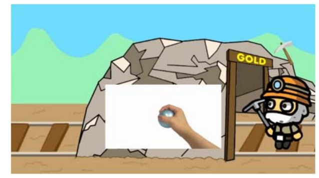


(a) Training: flickering stimuli only without game background (S_only)

(b) Game with BCI interaction (G+I)



(c) Game without BCI interaction (G-I)



(d) Non-flickering (NonF)

Fig. 2. Experimental design (a) Training condition for the classifier design to assess if stimuli were being attended to. (b) The game program that provided rewards for stimulus observation. (c) The game program without feedback for stimulus observation. (d) The conventional action observation training with non-flickering action videos and no stimulus feedback.

provide feedback. However, the goal of an action observation neurofeedback system is to activate the MNS in patients with stroke; therefore, providing feedback on the amount of MNS activation may not be appropriate, as patients may have deficits in MNS activation. Research has shown that some patients experience full or partial loss of performance following myocardial infarction (MI) after stroke [23]–[25]. Moreover, patients with stroke might show differential brain activation in the same task because of the site of their lesion [26]. Our goal was to propose a brain-computer interface (BCI) game-based interactive paradigm to facilitate the activation of the MNS in patients with lack of MNS activation by providing them with the experience of suitable action observation training. In this training, the patients could obtain proper interaction paradigm regarding their watching so that the system encouraged them to watch the action video to activate the MNS.

For robust application, we adapted the integrated steady-state visual evoked potential paradigm (SSVEP) with the action video paradigm for evoking the SSVEP and MNS simultaneously [27]. Following this, we implemented a BCI-based action video watching game that responds to the user's attention to the action video, in which users watch a flickering action video and obtain real-time feedback regarding their engagement. We evaluated the ability for this game paradigm to preferentially activate the MNS by investigating the strength and time course of mu suppression in the motor cortex.

## II. Methods

### A. Subjects

We recruited 15 healthy adults (four men and eleven women) in this study (IRB number: 40525-201612-HR-140) and informed consent was obtained from all participants. The mean age was 21.87 years ($\pm$2.07 years). Fourteen subjects were right-handed, and one subject was ambidextrous, based on a self-report measure. There was no compensation for participating in the experiment.

### B. Video Stimuli for Action Observation (Stimuli)

Short video clips of picking up a ball with the left and right hands were used as the action observation stimuli (Fig 1). The length of the video clips was 10 s, and each clip included three repetitions of picking up the ball. The background pixels flickered white and black during the clip. The interframe interval was 1/60 s and 1 period included six frames; therefore, the flickering frequency was 10 Hz (four frames up and two frames down out of six frames for 66.67% duty).

### C. EEG Data Acquisition

EEG data were collected from 32 dry electrodes using a g.Nautilus (g.tec medical engineering GmbH, Schiedlberg, Austria). EEG electrodes were arranged according to the international 10–20 system. Data were sampled at a rate of 250 Hz. The quality of the EEG signal was verified before the experiment. Subjects were instructed to view a stimulus displayed at the center of an LCD screen, which was positioned approximately 50 cm away. The stimulus had a resolution of 1920 x 1080 pixels and a vertical refresh rate of 60 Hz.

### D. Experimental Design

The experiment consisted of four conditions (Fig 2). Stimuli were shown 20 times in all conditions. Left- and right-hand action videos were provided in a pseudorandomized order. A rest was allowed between stimuli for 10 s. All conditions lasted for 400 s. Each condition was randomly provided and the training (S_only) condition preceded the game with BCI interaction (G+I) condition.

*1) Training: Flickering Video Stimuli Only Without Game Background (S_only):* In this condition, a flickering action video clip was shown at the center of the screen with a black background. It was designed to classify whether the stimuli were being attended to.

*2) Action Observation Game With BCI Interaction (G+I):* This condition classified whether subjects watched the stimuli and provided rewards for stimulus watching (Fig 3). First, participants were asked to watch an explanatory video that described how to play the game. Then, they were asked to play the game. In the game, feedback was provided on the participant's observation score and observation time. A score of zero represented no observation, and a perfect score, 100, represented full attentiveness for the whole clip. In addition, this condition provided real-time feedback on observation performance for the user during gameplay.

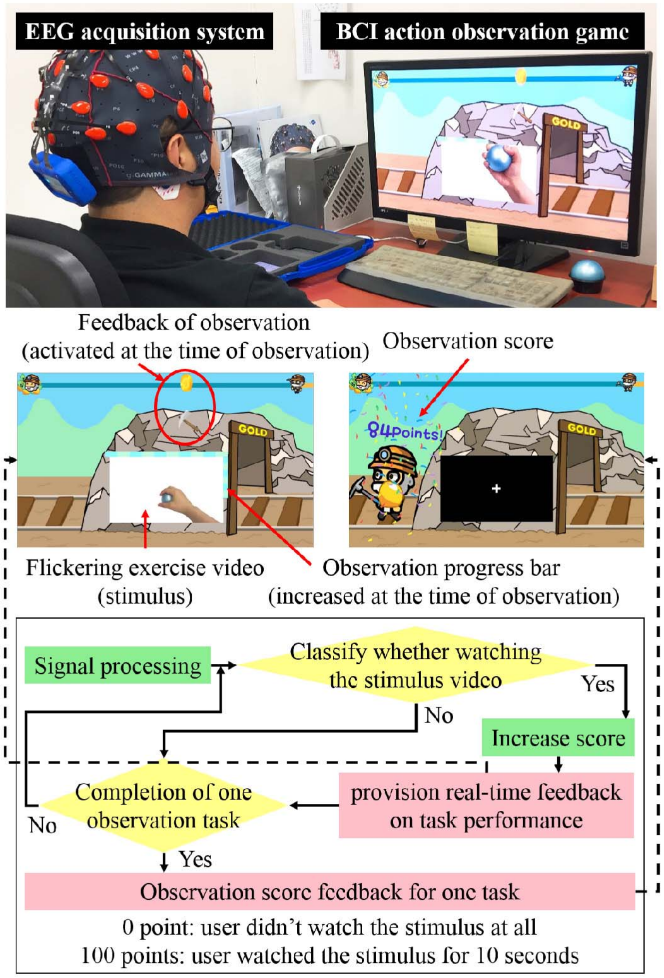



Fig. 3. System flowchart for a single observation task. The task was repeated 20 times per condition.

*3) Action Observation Game Display Without Interaction (G−I):* This condition used the same game program as the G+I condition but did not measure the participants attentiveness and always provided a perfect score to the user. This condition was a training (S_only) condition that included the flickering board and animated background.

*4) Non-Flickering Stimuli With Game Background (NonF):* The non-flickering condition used a non-flickering video as a stimulus; the background pixels of the clip showing the hand picking up the ball were white. An image of the game screen was used as the background screen. There was no feedback on participant watching. This condition was the same as a conventional action observation training program in which the participant just watches a video clip.

## E. Classifier Design and Process of Classification

Classification was conducted using the openVIBE software platform (ver. 1.2.0). Individual classifiers were designed to identify the stimulus observation and rest state of participants and ensure that they were attending the stimuli.

The common spatial filters (CSFs) and classifier were designed using data from the training (S_only) condition. First, the CSFs were created. Nine channels (C3, Cz, C4, Pz, PO3, PO4, PO7, PO8, and Oz) were selected for extracting features, and EEG data were separated between the two groups (1: left and right-hand video; 2: rest). The first 1-s of data from the start of the stimulus was removed to offset any delay in attention. The data were filtered for the SSVEP (9.5–10.5 Hz) and mu (8–13 Hz). Then, the two CSP filters were created using filtered signal types. The CSP filters were of the second order. Classifiers were designed, and data obtained from the nine channels were separated into two states and passed through the temporal filter for the SSVEP (9.5–10.5 Hz) and mu (8–13 Hz) in a manner equivalent to designing the CSF. Then, we passed the data through each CSF. Time-based epoching was performed with a 1-s duration and 0.1-s interval, and the average power of each epoch was obtained. A feature vector was created using the features obtained, which trained the classifier. A support vector machine algorithm was used, and the kernel type was linear. Ten partitions were used in the K-fold cross-validation test.

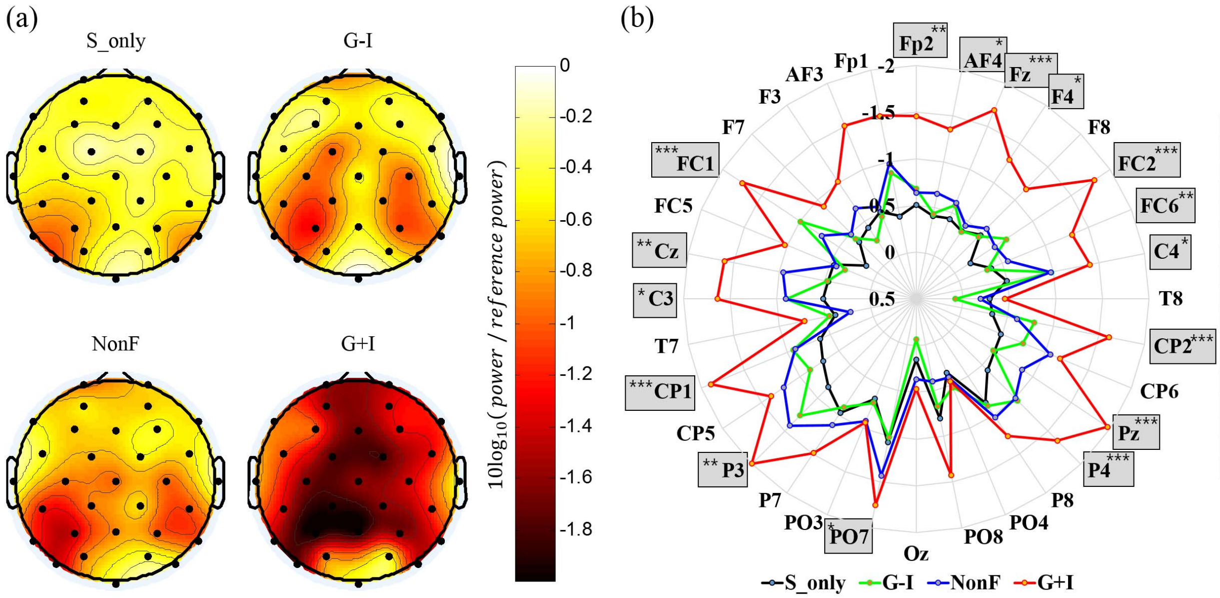
The CSF and classifier were used in the G+I condition. Data from the nine channels were acquired in real time and passed through the temporal filter for the SSVEP (9.5–10.5 Hz) and mu (8–13 Hz). Following this, data were passed through each CSF, and time-based epoching was performed with a 1-s duration and 0.1-s interval. The average power of each epoch was obtained, and the feature vector was created using these features. The individual classifier identified the state using the created feature vector, which was used for classification in this condition.

## F. EEG Analysis and Validation of Its Applicability

*1) The Analysis of MNS Activation:* The power of the mu band (8–13 Hz) in the observed EEG spectrum in each condition was analyzed to evaluate the effectiveness of the proposed system in relation to MNS. The average power of the mu band of resting epochs in the training (S_only) condition was used as the reference power of the mu power; therefore, mu suppression was represented by the log ratio of the mu band power to the reference power. This means that zero on this log-ratio represents no mu suppression and a negative value represents mu suppression. A positive value would represent the augmentation of the mu power; however, this case was not considered in this study.

*a) Mu suppression for each condition:* To extract the power of the mu band for each condition in C3 and C4, short-time Fourier transform (STFT) with a 1-s window size and 90% overlap was performed on the data obtained while the flickering stimuli were shown. The power of the mu band was extracted from the STFT, which was then averaged. After extracting the power of the mu band for each condition (S_only, G−I, NonF, and G+I), the log-ratio of the mu band power comparing the stimuli to the reference was calculated, which represented the amount of mu suppression when compared with the resting state. Differences among the values were statistically analyzed using repeated measures (rm) ANOVA.

*b) Analysis of the time course of mu rhythm suppression for each condition:* STFT with a 1-s window size and 90% overlap analysis was conducted with data from C3 and C4 during the




| channel | F | p |
|---|---|---|
| Fp2 | 4.309 | .010 |
| AF4 | 3.54 | .023 |
| Fz | 8.415 | .000 |
| F4 | 3.618 | .021 |
| FC1 | 8.074 | .000 |
| FC2 | 7.32 | .000 |
| FC6 | 5.328 | .003 |
| C3 | 3.624 | .021 |
| Cz | 7.613 | .004 |
| C4 | 2.894 | .046 |
| CP1 | 6.136 | .001 |
| CP2 | 9.371 | .000 |
| P3 | 5.972 | .002 |
| Pz | 10.18 | .000 |
| P4 | 6.64 | .001 |
| PO7 | 4.465 | .025 |

Fig. 4. (a) Topography of mu rhythm suppression (left four topographies) and rmANOVA main effects displayed in radial form (right graph). In the graph, each line represents the amount of mu suppression and the red line shows superior suppression in several channels, while the marked gray box represents significant main effects. The statistical values are displayed beside the graph.

total condition period, which was 400 s, to measure the time course of mu suppression. We extracted and averaged the power of the spectrum between mu bands and obtained the log-ratio calculation to create a mu suppression index. After calculating the mu suppression index for each participant, the values were averaged to create a group mean. The time course of mu suppression was displayed for each condition. For the convenience of analysis, we used a 60-s point moving average filter so that we could compare the trend by smoothing the time course analysis.

*2) BCI Game Performance Evaluation:* To evaluate the performance on the BCI game proposed in this study, we investigated the classifying accuracy and subjective responses of participant experience relative to the level of engagement and boredom. We found that the classifying accuracy for our classifier was $82.02 \pm 8.72\%$ when a 10-fold cross validation test was conducted.

For the subjective responses, the participants were asked to answer to questions regarding their level of engagement and feeling of boredom on a Likert scale (strongly agree = 5, not at all = 1). To compare these scores among conditions, we performed paired t-tests for each pair of conditions.

## III. Results

Mu rhythm suppression was observed under all four conditions (Fig 4). The rmANOVA showed a significant main effect in both C3 ($F = 3.624$, $p = 0.021$) and C4 ($F = 2.894$, $p = 0.046$). In the post-hoc analysis, the G+I condition was strongly suppressed in Mu rhythm compared to G−I and S_only for C3 and to S_only for C4.

Mu suppression was confirmed using the topography of mu rhythm suppression (Fig 5). Mu rhythm suppression was observed in most areas. This suppression was strongly observed in the frontoparietal area and prominently observed in the game condition (G+I).

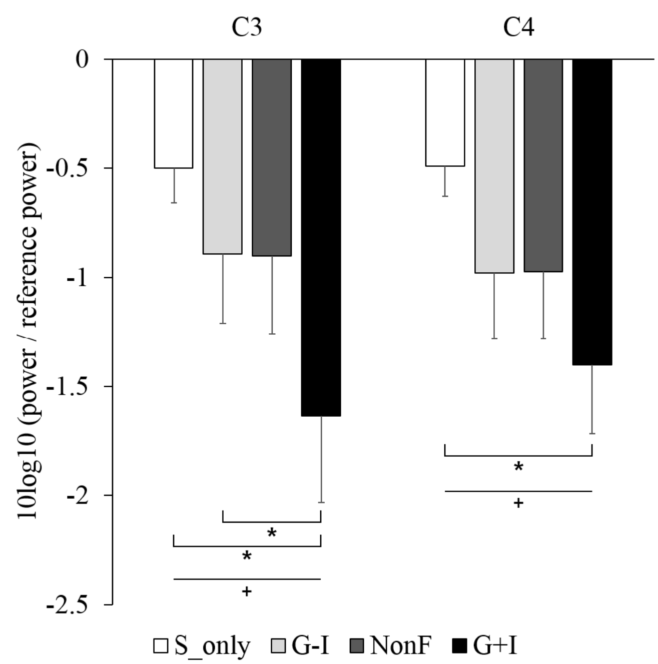



Fig. 5. Mu rhythm suppression in the C3 and C4 channels in each condition. Zero = no change, negative numbers = mu suppression. The game condition (G+I) resulted in the largest mu power suppression. "+" represents the significant main effect in the rmANOVA among the four conditions at $p < 0.05$. "*" corresponds to the post hoc comparison results with $p < 0.05$.

All 32 channels were compared among the four conditions. The rmANOVA revealed main effects in several channels and, in the G+I condition, the mu rhythm was superiorly suppressed (See Fig 5 for the detailed statistical results). As shown

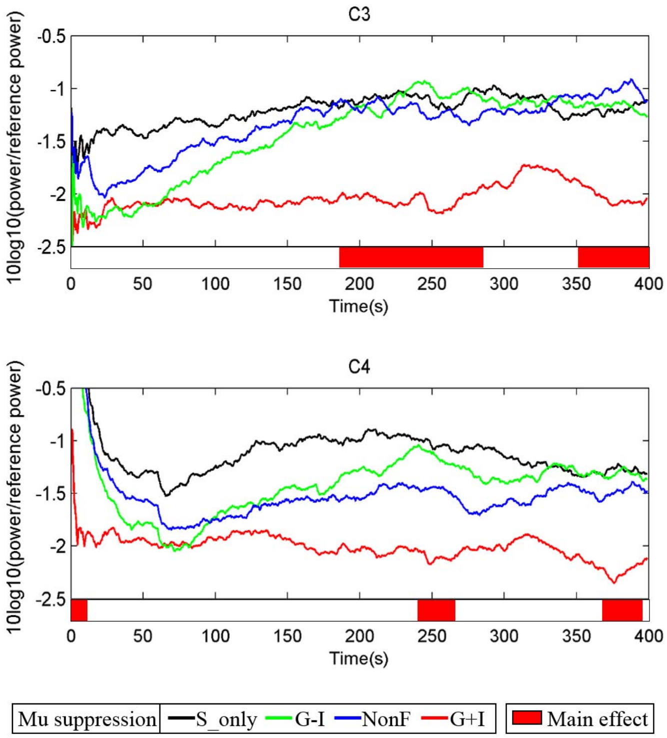



Fig. 6. Changes in mu suppression in C3 and C4 over time. The x axis represents elapsed time from the start of the experiment. Each condition lasted for 400 s. The y axis represents the mu rhythm suppression as a log ratio. The color of the line represents each condition. The bar graph below the line graph represents the significance of the main effect in the rmANOVA among conditions.

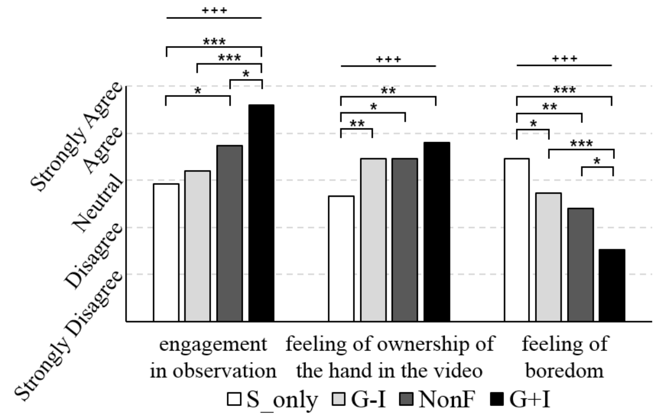



Fig. 7. Results of the program satisfaction evaluation. "+++" represents a significant main effect in the rmANOVA among the four conditions at $p < 0.001$. "***" corresponds to the maximum significant difference, $p < 0.001$, "**" to $p < 0.01$, and "*" to $p < 0.05$.

in the graph in Figure 5, the outermost red line, representing the G+I condition, denotes the stronger mu suppression in the various channels, while the other lines (black for S_only, green for G−I, and blue for NonF) denote that the other conditions resulted in weaker suppression.

The time course of mu suppression over 400 s in C3 and C4 is shown in Figure 6. All four conditions showed suppression of the mu rhythm. Interestingly, three conditions, S_only, G−I, and NonF, showed a time-dependent reduction in mu suppression. The G+I condition was associated with a constant level of mu suppression. The red bar under the time course graph indicates the significance of the main effect as found with the rmANOVA at $p < 0.05$. The differences became statistically significant with the passage of time in C3.

The subjective responses to the attentiveness questionnaire showed that the participants were mostly engaged during the G+I condition. (Fig. 7). All three items showed significant main effects (engagement in observation: $F = 10.661$, $p = 0.000$; feeling of ownership: $F = 6.279$, $p = 0.001$; feeling bored: $F = 10.787$, $p = 0.000$). In the post hoc analysis, the G+I condition showed superior engagement compared to other conditions; next, the engagement in the NonF condition was significantly different from that in the S_only and G+I conditions. Regarding the feeling of ownership of the hand in the video, the participants provided a significantly higher score for the G+I condition compared to the other conditions. Subjects reported feeling less bored in the G+I condition and the feeling of boredom increased in the order of the NonF, G−I, and S_only conditions.

## IV. Discussion

This study proposed a BCI-based action observation rehabilitation game paradigm that could maintain one's attention during watching effectively to enable the activation of the MNS. In the game, we designed a program that detected watching an action video clip using the SSVEP and ERD that were simultaneously evoked by a flickering action video and game program, which provided responses based on the participants' watching. To validate the effectiveness of this paradigm, MNS activation, represented by mu suppression [28], was compared among the S_only, G−I, G+I, and NonF conditions. We found that mu suppression was observed in all conditions, but prominent suppression was observed in the G+I condition.

The G−I and NonF conditions differed based on whether the action video clip was flickering; therefore, we could ascertain whether the flickering itself might affect brain activation, such as mu suppression. However, our results found no significant difference in the amount of mu suppression between these conditions, suggesting that flickering does not affect brain mu suppression and therefore, a flickering action video paradigm can be applied to the rehabilitation scheme using MNS activation, such as the action observation intervention method.

Importantly, we observed prominent mu suppression in the G+I condition when compared with the other conditions. The game condition differed from the other conditions because it has more interactive feedback and attractive gaming display. This display might be more attractive to watch and more familiar to the participants, which may be the reason for the increased attentiveness. However, when we compared the S_only condition with the G−I conditions, the S_only condition showed slightly lower but nonsignificantly different levels of attentiveness. This suggests that the gaming display may not be a critical factor in engagement.

The final difference of the G+I condition related to the feedback that participants obtained introduced interactive gameplay and added meaning to the participants' experience [22]. In the game, participants obtain feedback that relates to their level of attentiveness; therefore, participants are incentivized to gain higher scores. This suggests that the game paradigm responding to the participant's intention is more effective at activating the MNS than watching action video clips. The gaming factor, participant interaction, may enhance engagement and result in increased attentiveness and facilitation of brain function [29]. The closed loop that this game facilitates between the computer and participant performing this specific task enables the participants to measure their own progress and achieve goals. Continuing to monitor their progression would further engage the participants in the task, reducing their level of boredom and maintaining attentiveness to the task for a greater length of time. In our game, the progress display and scores after trials played this role, which incentivized participants to remain engaged and obtain higher scores. Therefore, the gaming factor induced more attentiveness, and more attentiveness would result in stronger mu suppression [30]. Although objective monitoring regarding attention while experiencing the sessions was not conducted, the subjective response of high engagement and the stronger mu suppression may support that the gaming factor could capture one's attention during the session.

To investigate whether the participant's attentive state and MNS activation could be maintained through the session, we plotted the time course of mu suppression for each condition. In the early phase of all the conditions, there was a similar amount of mu suppression, with no significant differences among groups; however, mu suppression decreased over time in the S_only, G−I, and NonF conditions, suggesting that the participants had difficulty maintaining attentiveness while the action video was displayed.

Conversely, mu suppression was maintained in the game condition, and it was significantly greater when compared with the mu suppression in the other conditions in the late phase of the video. This suggested that the participants maintained their engagement through the G+I condition. In addition, the topography of mu suppression was strongest in the channels corresponding to the frontoparietal region in addition to the motor cortex (C3 and C4) in the G+I condition. The frontoparietal regions participate in the attention network in the human brain [31]. They are mostly activated during a task requiring spatial [32], internal [33], or selective attention [34]. This frontoparietal strong involvement in mu suppression in the G+I condition would support that subjects experienced the G+I condition in a more attentive manner. Moreover, the frontoparietal regions are involved in the representation and comprehension of observed actions [35] by constructing an abstract representation of action outcomes [36]. We consider it possible that the participants would establish an abstract association between watching the action and earning gold in the game so that they could accomplish the goal of the game in the G+I condition.

Therefore, we hypothesize that this pattern of mu suppression is accomplished by motivating the participants with feedback (gaining (high score) or losing (low score) gold) dependent upon their level of attentiveness. In addition, the supporting data from the questionnaire showed that the participants were least bored and most engaged in the G+I condition compared with the other conditions. This could facilitate goal-directed behavior in the participants toward attentiveness that enhances the SSVEP power [37], [38] and mu suppression [28]. These factors promote classification, enable more accurate feedback, and encourage the participants to perform better by remaining attentive to the video clip for the whole session. In addition, this may explain the stationary large mu suppression pattern in the G+I condition.

In conclusion, the flickering action video paradigm was successfully applied to the game paradigm, and by integrating the action observation paradigm with BCI technology that provided feedback to the participants, engagement was enhanced. This suggests that this paradigm can elicit enhanced activation of the MNS and it could be employed to obtain positive intervention outcomes. This paradigm could be applied to patients who have MNS dysfunction who could benefit from action observation. Actually, patients with autism [39], [40] or schizophrenia [41], [42], as well as stroke, could primarily benefit from MNS facilitation through action observation. Regarding patients with autism or schizophrenia, as their deficits mostly concern emotional processing [43] or social ability [41], [44] rather than movement ability, the video content should be adapted accordingly to social or emotional and further research would be necessary. Moreover, more effective applications that engage participants could be achieved by integrating the flicking paradigm into a virtual reality system, in addition to various action video clips.

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