Chapter

Applications of Brain-Computer Interface in Action Observation and Motor Imagery

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Abstract

Motor imagery (MI) and action observation (AO) are vital elements in brain-computer interface (BCI) applications. MI involves mentally simulating movements and physical execution, while AO involves observing others perform actions. Both activate crucial brain areas linked to movement, making them valuable for BCI-assisted motor rehabilitation. This chapter explores studies in sports, occupational therapy, and neurorehabilitation, focusing on combining AO and MI (AO + MI) in BCI applications. Results show the positive impact of AO + MI interventions on motor performance aspects such as imagery ability, reaction time, and muscle activation across various tasks. The fusion of virtual reality (VR) with MI proves potent in neurorehabilitation, especially in stroke and Parkinson's disease rehab and cognitive enhancement. Additionally, VR-based AO combined with kinesthetic motor imagery (KMI) influences cortical activity, refining brain patterns and task performance. These findings suggest that combining VR-based action observation with KMI can significantly enhance BCI-assisted motor rehabilitation for individuals with motor deficits. This approach holds promise for improving motor control and fostering neuroplasticity.

Keywords: virtual reality (VR), kinesthetic motor imagery (KMI), brain-computer interface, EEG, event-related (De-) synchronization, machine learning, action observation, neurorehabilitation

1. Introduction

Motor imagery (MI) is the cognitive process of mentally simulating a particular movement without physically executing it. Within the realm of brain-computer interface (BCI), MI has garnered considerable interest as a promising therapeutic technique for augmenting motor recovery in individuals facing neurological challenges like stroke, spinal cord injury, and Parkinson's disease (PD). By activating the brain's motor networks through mental rehearsal, MI can contribute to the rewiring of neural circuits, fostering functional improvements.

The engagement of similar brain regions as those involved in actual movement execution, such as the primary motor cortex, premotor cortex, supplementary motor area, and cerebellum, characterizes the practice of motor imagery. This engagement facilitates neuroplasticity, enabling the brain to reorganize and form new connections, ultimately promoting motor skill acquisition and rehabilitation.

In the realm of motor rehabilitation, action observation (AO) and MI have traditionally been studied as distinct phenomena. AO entails observing others perform specific movements, while MI involves mentally envisioning oneself executing those same movements. Both methods activate brain areas crucial for movement execution, making them valuable in motor rehabilitation. Recent research, however, has unveiled the potential benefits of merging AO and MI, known as AO + MI, in enhancing motor performance and facilitating learning. This integrative approach has garnered attention across diverse domains, including sports, occupational therapy, and neurorehabilitation, especially within the context of BCI applications.

1.1 Action observation and motor imagery in sports and skill learning

The intersection of BCI and sports performance research has witnessed a notable upswing, particularly in the exploration of action observation and motor imagery to amplify both motor skills and imagery capabilities. This interdisciplinary approach, merging cognitive and motor processes, has been investigated across diverse sports disciplines, each providing unique insights.

In the world of golf, Marshal and Wright [1] strategically delved into the precision-oriented sport, where mental imagery holds a pivotal role. Their study aimed to discern the effectiveness of layered stimulus-response training (LSRT) in comparison to the combined impact of AO + MI. The findings illuminated not only the nuances of golf putting performance but also set a precedent for the prospective applications of AO + MI in various sports, especially within the context of BCI applications.

Turning to basketball, a dynamic sport requiring a fusion of skill and split-second decision-making, Robin et al. [2] embarked on an exploration combining dynamic motor imagery (dMI) with physical practice and model observation. Their focus was on discerning the impact of this combination on advanced basketball players' free throw performances. The study probed the intricate balance between mental visualization and physical execution, providing insights into the synergistic effects of dMI and AO + MI. Dart-throwing, another precision-centric sport, was scrutinized by Romano Smith et al. [3], investigating the impact of simultaneous action observation and motor imagery (S-AO + MI) on performance. The meticulous nature of dart-throwing, where slight variations can lead to significant outcome differences, made it an apt choice to study the granular effects of S-AO + MI.

Expanding beyond specific sports, Sirico et al. [4] delved into the broader cognitive implications of AO + MI. Their study examined the influence of AO + MI on reaction time (RT) to both visual and auditory stimuli, offering insights into scenarios where rapid reactions are paramount. In a comprehensive approach, Chye et al. [5] conducted meta-analyses to quantify changes in corticospinal excitability and motor skill performance with AO + MI interventions, presenting a holistic view of its efficacy in motor learning.

Binks et al. [6] delved deeper into motor learning intricacies, investigating the training effects of AO + MI instructions on a complex cup-stacking task. Their study suggested that even complex motor skills, traditionally relying heavily on physical practice, can witness significant enhancements through cognitive interventions like AO + MI. On the technological front, Ono et al. [7] merged neurofeedback and AO + MI, exploring the potential of neurofeedback training of MI under action observation with a focus on proprioceptive feedback. This fusion aimed to enhance MI-induced event-related desynchronization (ERD), promising avenues for future research.

Innovation continued with Castro et al. [8], introducing sonification to the AO + MI discourse. Their study explored the effects of sonification on AO + MI during a practice block, delving into the auditory domain and investigating how sound cues intersect with motor learning.

Across these diverse studies, consistent themes emerged. Marshal et al.'s [1] findings highlighted the LSRT group's marked improvement in golf putting performance compared to AO + MI and control groups. Robin et al.'s [2] basketball-centric research revealed the Model + imagery group's outperformance in free throw performance, combining imagery with model observation. Romano Smith et al. [3] found that the S-AO + MI group, engaged in dart-throwing, exhibited significantly greater improvements, suggesting more efficient movement patterns. Sirico et al.'s [4] broader study indicated AO + MI training's positive impact on reaction times to auditory stimuli. Chye et al.'s [5] meta-analyses underscored the positive effects of AO + MI on both corticospinal excitability and motor skill performance. Binks et al.'s [6] findings on the cup-stacking task suggested that AO + MI instructions could significantly enhance movement execution times. Ono et al.'s [7] exploration into neurofeedback training indicated enhanced MI-ERD power with proprioceptive feedback. In contrast, Castro et al.'s [8] study on sonification hinted at the potential distractions it might introduce in the AO + MI process. This collective body of research illuminates the multifaceted and promising landscape of integrating AO + MI within the BCI framework for enhancing cognitive and motor functions.

1.2 Neurorehabilitation

In neurorehabilitation, BCI plays a crucial role as it creates a direct connection between the brain and outside equipment. BCIs allow people with neurological abnormalities to participate in movement therapy, cognitive training, and communication through accurate decoding of brain signals. BCI-assisted motor imagery activities support neuroplasticity and aid in motor recovery, enabling users to operate external equipment like exoskeletons and robotic limbs.

Stroke often leads to motor dysfunction, and while rehabilitation therapy can help patients regain some function, many still experience chronic impairments. De Vries and Mulder [9] conducted a study exploring the evidence for using motor imagery and action observation as new approaches to stroke recovery. The study suggested that motor imagery and observation could lead to functional recovery and plastic changes in patients who have had a stroke. Wright et al. [10] conducted a study comparing the effects of action observation and motor imagery on corticospinal excitability. The researchers found that combining action observation and motor imagery resulted in greater facilitation of corticospinal excitability compared to observation or imagery alone. This finding suggests that the integration of action observation and motor imagery may be more beneficial for stroke rehabilitation.

Postural control and balance are crucial for daily activities and preventing falls, especially in individuals who have been immobile due to stroke or other conditions. Taube et al. [11] conducted a study investigating the effects of motor imagery and action observation on postural tasks. The research revealed that both techniques could enhance motor performance and activate brain regions essential for balance control. One area where the effectiveness of non-physical balance training has been demonstrated is in enhancing postural control in young people. However, little is known about the potential for mental simulation to increase corticospinal excitability in lower leg muscles. Mental simulation of isolated, voluntary contractions of limb muscles has been shown to increase corticospinal excitability. On the other hand, more automated tasks such as walking appear to have minimal effects on motor-evoked potentials (MEPs) elicited by transcranial magnetic stimulation (TMS).

A study by Mouthon et al. [12] aimed to investigate how AO and MI of balance tasks change corticospinal activity. The study found that AO combined with MI (AO + MI) facilitated the greatest number of MEPs, followed by MI alone and passive AO. Interestingly, MEP facilitation was significantly higher during dynamic balancing tasks compared to static standing tasks. This suggests that the nature of the mental simulation and the difficulty of the task both affect corticospinal excitability during mental simulations of balance tasks. These findings have implications for optimal training and rehabilitation effects, indicating that combining MI and AO during challenging postural tasks may lead to better outcomes.

Parkinson's disease is characterized by a progressive decline in motor skills and autonomy in daily living tasks. While physiotherapy is often recommended as an adjunct treatment, there is a need for innovative rehabilitation methods with increased long-term effectiveness. Abbruzzese et al. [13] proposed motor imagery and action observation as potential rehabilitation techniques for PD patients, as they engage the same neural network involved in motor execution and learning.

Developmental coordination disorder (DCD) is a condition characterized by motor control problems. Scott et al. [14] explored the use of action observation and motor imagery in children with DCD. The research indicated that AO + MI resulted in increased neurophysiological activity in the motor system and improved motor skill acquisition compared to using either technique independently.

The internal modeling deficit (IMD) theory proposes that DCD motor control problems stem from poor predicted motor control. Marshal et al. [15] conducted a study to investigate the effectiveness of a combined AO + MI intervention in enhancing eye-hand coordination and reducing deficits in internal modeling during a visuomotor rotation task. The study involved 20 children with DCD who were randomly assigned to either the AO + MI group or the control group. The results demonstrated that the AO + MI group exhibited speedier completion times, more target-focused eye movement behavior, and cleaner movement kinematics compared to the control group. These findings provide support for the IMD hypothesis and suggest that AO + MI interventions may help to reduce deficits and enhance motor performance in children with DCD.

Rehabilitation professionals often employ MI and AO techniques to improve physical strength, prevent injuries, and aid in recovery. Recent studies have highlighted the benefits of combining AO and MI in enhancing motor coordination, learning activities of daily living (ADLs), and increasing corticospinal excitability. This chapter delves into the effectiveness of AO and MI interventions, their impact on motor strength, coordination, and excitability, and their potential applications in rehabilitation and motor learning. Scott et al. [16] conducted a study comparing the gains in hamstring force for MI during AO to two MI-only training groups. The results showed that AO+ MI training significantly increased hamstring strength, predominantly in the right limb. This finding suggests that the combination of AO and MI is more effective than MI alone in preventing injuries and aiding in rehabilitation. In another study by Scott et al. [17], the effectiveness of a home-based, parent-led AO + MI intervention for teaching ADLs to children with DCD was examined. The results revealed that the AO + MI intervention significantly improved task completion times and movement techniques for tasks such as shoelace tying and cup stacking. Moreover, a higher percentage of children who received the AO + MI intervention successfully learned the skill compared to those in the control group. These findings suggest that AO + MI therapies can be beneficial in supporting the development of motor abilities in children with DCD.

Sakamoto et al. [18] investigated the impact of combined action observation and imagery on corticospinal excitability. The study found that simultaneous observation and imagery of an action increased corticospinal excitability compared to observation or imagery alone. However, this enhancement was only achieved when the observed and imagined actions had consistent phase relationships. These findings highlight the importance of maintaining consistent phase relationships for effective motor learning through AO and MI. Liepert and Neveling [19] explored the effects of motor imagery and action observation on the motor excitability of foot movements. Their findings revealed that both MI and AO increased corticospinal excitability, with MI being more effective. Additionally, MI induced a disinhibition of motor cortex activity. These results suggest that MI and AO interventions can enhance motor excitability and may aid in the restoration of motor deficits in neurological disorders. Macuga and Frey [20] conducted an fMRI study to investigate the distinct neural representations supporting observation, imagery, and synchronous imitation of a finger-tapping task. The results showed that each condition had a unique neural signature. Synchronous imitation exhibited enhanced bilateral activity in the cerebellum, supplementary motor area (SMA), and parietal operculum, while observation was associated with greater increases in caudal SMA activity, indicating partially independent mechanisms for each behavior. These findings collectively underscore the multifaceted benefits of AO and MI interventions, their impact on motor strength, coordination, and excitability, and their potential applications in rehabilitation and motor learning, particularly within the context of BCI advancements.

2. Understanding the neurocognitive processes behind AO + MI

Applications of BCI that make use of MI and AO have shown considerable promise in a variety of neurorehabilitation settings. Thus, the incorporation of AO and MI into BCIs offers a flexible and efficient method of neurorehabilitation, tackling the complex issues related to stroke, Parkinson's disease, postural control, balancing tasks, and developmental coordination deficits.

The intricate dance between the brain and body has always been a subject of fascination. Studying the brain has taken us a step closer to understanding this complex relationship, particularly in the realm of AO and MI. While we have made significant strides in pinpointing where cortical activities are activated during these processes, the modulation of cortical activity, especially in relation to the observed or imagined phases of movement, remains relatively uncharted territory.

Kaneko et al. [21] embarked on a journey to bridge this knowledge gap. Their study, which employed electroencephalography (EEG) to record cortical activity, centered on the observation of walking. The participants were tasked with simply observing the act of walking or observing it while simultaneously envisioning themselves in the act. The results were intriguing. Alpha and beta power in the sensorimotor cortex diminished during both AO and AO + MI. More importantly, the modulations in power spectral were found to be walking phase-dependent, with AO + MI modulations closely mirroring those observed during actual walking. This revelation deepens not only our understanding of the neural mechanisms underpinning walking but also offers a beacon of hope for rehabilitating patients with neurological gait dysfunctions.

Jeannerod's [22] early studies provided an integrative perspective on AO and MI, emphasizing the shared neurocognitive processes that underlie both phenomena. Over the past two decades, while AO and MI have been subjects of independent research, recent findings have pointed toward an increased cortical activity when both are conducted simultaneously. Vogt et al. [23] took this understanding a notch higher by introducing the concept of a spectrum of concurrent AO + MI states. This spectrum, which ranges from congruent to conflicting AO + MI, offers a comprehensive framework to fathom the overlap and coordination between observed and imagined actions. Meers et al. [24] further delved into this intricate relationship by employing transcranial magnetic stimulation-induced motor-evoked potentials. Their study juxtaposed congruent AO + MI, where the observed and imagined actions were in harmony, against incongruent AO + MI, where they were at odds. The findings were revelatory. While congruent AO + MI amplified the facilitative effects in the task-related effector engaged in MI, incongruent AO + MI showed no such enhancement. This challenges the long-held belief of primary motor cortex simulation.

Eaves et al.'s [25] research took a slightly different route, exploring how various MI techniques during AO influenced the automatic imitation (AI) effect. The results were clear: MI could modulate the effects of AO on subsequent execution. Another study by the same group [26] delved deeper into the electrophysiological correlates of AO + MI, uncovering that both synchronized and static AO + MI produced more robust motor activations than single-action simulation. Bruton et al. [27] introduced the dual-action simulation hypothesis, suggesting that an observer's brain can simultaneously represent an observed and imagined action. Their experiments provided empirical support for this hypothesis, shedding light on the cognitive and attentional mechanisms that drive the effects of AO + MI. Eaves et al. [28] further explored the nuances of practicing motor actions through MI, enhanced via synchronous action observation. Their comprehensive review touched upon the behavioral effects of AO + MI practice in the early phases of skill acquisition, the selection and presentation of suitable models, and the effects of expertise. Their findings underscored the facilitative effects of AO + MI practice on motor actions, paving the way for future research. Lastly, Villiger et al. [29] turned their attention to the role of observation and imagination in motor execution. Their study, which used functional MRI (fMRI), found that the combination of observation and imagination could activate the motor execution network even without any overt movement. This revelation has profound implications, especially for the development of virtual reality (VR) interactions in neurorehabilitation and motor task training.

2.1 Results and implications

The collective findings from these studies paint a promising picture. The diminished alpha and beta power in the sensorimotor cortex during AO and AO + MI, as observed by Kaneko et al., offers a deeper understanding of the neural mechanisms of walking. The spectrum of concurrent AO + MI states proposed by Vogt et al. [23] provides a comprehensive framework for future research. Meers et al.'s [24] findings challenge traditional beliefs about primary motor cortex simulation, while Eaves et al.'s [25] research underscores the potential of MI to modulate the effects of AO. Bruton et al.'s [27] dual-action simulation hypothesis opens new avenues for understanding cognitive and attentional mechanisms, and Villiger et al.'s [29] insights into the role of observation and imagination in motor execution have profound implications for neurorehabilitation. The collective findings underscore the promising applications of AO + MI within the BCI framework, advancing our understanding and paving the way for innovative neurorehabilitation approaches.

3. The power of virtual reality in motor imagery: unlocking rehabilitation potential

In the contemporary landscape, the integration of BCI with MI has surfaced as a potent strategy in the realm of neurorehabilitation. Through the synthesis of BCI and MI within VR environments, this cutting-edge approach tailors experiences to the individual, offering personalized scenarios and real-time feedback. This progressive fusion harnesses the adaptability of the brain and incorporates the core tenets of action execution and observation to facilitate the restoration of motor function in individuals affected by conditions such as stroke or other neurological disorders. The outcomes of VR-based MI training have exhibited considerable promise, showcasing its effectiveness in augmenting motor control and fostering neuroplasticity for improved outcomes in neurorehabilitation.

3.1 The hybrid BCI-VR system

A groundbreaking study by Badia et al. [30] introduced a hybrid BCI-VR system that combined personalized motor training in a VR environment with neurofeedback employing mental imagery. This paradigm aimed to engage secondary or indirect pathways to access undamaged cortico-spinal tracts, enabling stroke patients to regain motor function. The study's findings revealed that simultaneous motor activity and motor imagery effectively engaged cortical motor areas and associated networks, enhancing subjects' control of their virtual avatars during training tasks.

Expanding on this research, Vourvopoulos et al. [31] investigated the same paradigm with multimodal VR simulations and motor priming (MP). The results demonstrated improved BCI performance for VR and MP conditions, suggesting that using both VR and MP techniques can enhance neural activation and promote neuroplastic changes.

MI has long been recognized as a robust foundation for the development of BCIs and VRs, offering new methods to overcome stroke-related motor limitations. BCIs and VRs, when combined, expand the possibilities of virtual rehabilitation, particularly for patients with a poor motor function who have limited access to care. Researchers have been driven to explore the potential of BCI-VR technology in search of more effective and dependable BCI control.

While MI-BCIs have shown promise, there have been challenges in terms of low bit transfer rate, BCI illiteracy, and suboptimal training procedures. To address these limitations, Skola and Liarokapis [32] created an embodied training environment using VR. Participants observed a human-like avatar from a first-person view, with the avatar's movements reflecting their MI actions. The study demonstrated that the embodied VR environment significantly improved BCI action accuracy compared to a control group trained with a standard MI-BCI training protocol.

Following this line of research, Škola et al. [33] developed a gamified MI-BCI training in immersive VR. By incorporating gamification, progressive training tempo, and reinforcement of body ownership transfer, the study aimed to enhance motivation, engagement, and focus during MI-BCI training. The results showed that the participants trained in the gamified VR environment achieved a basic level of MI-BCI operation, highlighting the effectiveness of this training approach.

Choi et al. [34] explored the use of immersive VR headsets in motor imagery training. By presenting egocentrically simulated virtual scenarios and action observation, the study aimed to investigate the training procedure's impact on user immersion and illusion. The analysis of participants' electroencephalogram (EEG) signals revealed that immersive VR headsets enhanced rhythmic patterns and spatial feature discrimination in the brain compared to traditional monitor displays. These findings suggest that immersive VR, with its illusion and embodiment, can effectively enhance motor imagery training.

3.2 VR-based motor imagery training for rehabilitation

VR has emerged as a promising tool in the realm of medical rehabilitation, offering immersive experiences that can be tailored to individual needs. Huang et al. [35] and Lin et al. [36] pioneered this approach for post-stroke rehabilitation by proposing VR-based motor imagery training systems. These systems were not just generic VR experiences; they were intricately designed with surface electromyography (EMG)-based real-time feedback. This feedback mechanism allowed for personalized training, ensuring that the rehabilitation process was tailored to the individual's unique needs. The immersive scenarios they crafted were centered around bilateral upper-limb basketball shooting practice, a dynamic activity that engages multiple muscle groups and requires coordination.

Beyond the realm of stroke rehabilitation, Kashif et al. [37] expanded the application of VR and MI to address the challenges posed by PD. Recognizing the debilitating effects of PD on balance, motor function, and even simple activities of daily living (ADLs), the study was designed to assess the combined impact of VR and MI on these critical areas. Meanwhile, the world of BCI games, when combined with VR, has been explored as a tool for cognitive enhancement. Bulat et al. [38] ventured into this domain, focusing on a P300-based BCI VR game. The game was not merely for entertainment; it was meticulously designed to engage and challenge cognitive processes.

3.2.1 Results and findings

The results from the studies by Huang et al. [35] and Lin et al. [36] were illuminating. They showcased the effectiveness of their VR systems in assessing the degree of involvement required for post-stroke rehabilitation. More importantly, they revealed discernible differences in muscle strength between various training conditions, underscoring the potential of their approach.

Kashif et al.'s [37] exploration into the combined effects of VR and MI for Parkinson's disease rehabilitation yielded encouraging results. When VR with MI methods was added to the regular physical therapy regimen, there was a marked improvement in motor function, balance, and ADLs. These improvements were significantly more pronounced than what was observed with physical therapy alone, highlighting the transformative potential of integrating VR and MI into PD rehabilitation.

Bulat et al.'s [38] foray into the world of P300-based BCI VR games for cognitive enhancement also bore fruit. Their study results indicated a positive uptick in selective attention and mental inhibition among healthy individuals. This suggests that such games, when combined with the immersive nature of virtual reality, can enhance not only specific cognitive functions in healthy subjects but also offer potential benefits for educational tasks, attention training, and even rehabilitation for those with mild mental disorders or the elderly.

The results illuminated the transformative potential of integrating VR and MI into post-stroke and PD rehabilitation, showcasing improvements in motor function, balance, and cognitive functions, suggesting broad applications in educational tasks, attention training, and rehabilitation for various populations.

4. Integrating AO within a VR environment with kinesthetic motor imagery

In a study by Lakshminarayanan et al. [39], the researchers investigated the effect of combining action observation in VR with kinesthetic motor imagery (KMI) on cortical activity (**Figure 1**). Previous studies have shown that VR-based action observation can enhance motor imagery by providing visual information and embodiment. Additionally, KMI has been found to produce similar brain activity to physically performing a task. The researchers hypothesized that utilizing VR to offer an immersive visual scenario for action observation while participants performed KMI would improve cortical activity related to motor imagery.

4.1 Experimental results

Fifteen participants performed KMI of three hand tasks (drinking, wrist flexion-extension, and grabbing) both with and without VR-based action observation. The results showed that combining VR-based action observation with KMI enhanced brain rhythmic patterns and provided better task differentiation compared to KMI without action observation. This suggests that using VR-based action observation alongside KMI can improve motor imagery performance.

The findings have important implications for rehabilitation paradigms aiming to improve motor functions. BCI assistive devices that utilize motor imagery training

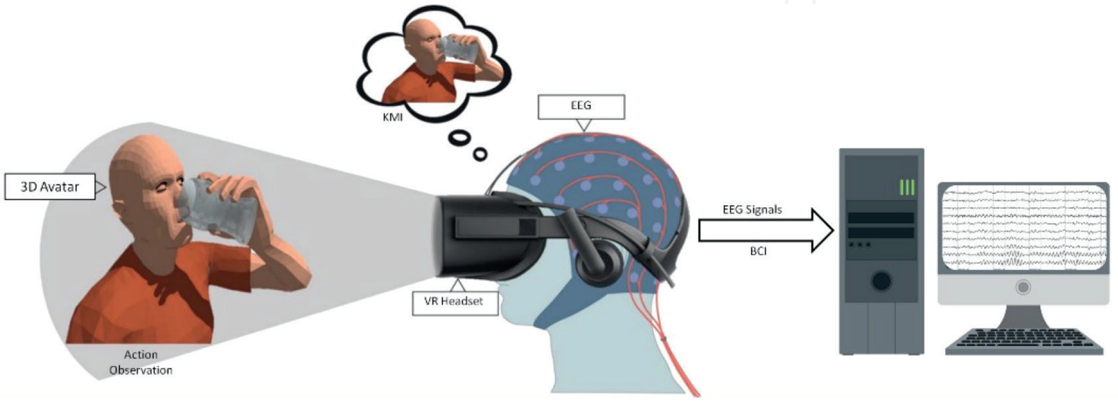

Figure 1.
BCI application in AO and KMI with VR integration.

have been shown to be effective in rehabilitating patients with motor deficits. By combining VR-based action observation with KMI, the researchers have demonstrated an enhanced cortical response during motor imagery. This could potentially improve the effectiveness of BCI-assisted rehabilitation for patients with motor deficits.

The study used EEG to analyze the differences in brain activity between VR-KMI and Non-visual aided (NVA)-KMI. The results showed an increase in event-related desynchronization (ERD) in the alpha and beta bands during VR-KMI compared to NVA-KMI. This indicates a greater activation of the sensorimotor cortex during VR-based action observation and KMI.

Furthermore, machine learning techniques were applied to discriminate between the different motor imagery tasks based on the EEG data. The classification accuracy was significantly higher for VR-KMI compared to NVA-KMI, indicating that VR-based action observation improved task discrimination during motor imagery.

4.2 Implications

Overall, this study highlights the potential benefits of combining VR-based action observation with KMI for motor imagery performance. The findings contribute to our understanding of the neural mechanisms underlying motor imagery and provide insights for the development of more effective rehabilitation strategies for patients with motor deficits.

5. Conclusion

Brain-computer interfaces have significant applications in motor imaging and action observation. BCIs improve the efficacy of AO and MI procedures in sports, rehabilitation, cognitive improvement, and neuroscientific research. The integration of AO and MI stands as a revolutionary approach in the domain of motor learning and rehabilitation, consistently proving more effective in enhancing complex motor skills than individual applications of either technique. This synergistic approach maximizes not only the benefits of mental simulation but also holds promise for optimizing motor skills, whether for rehabilitation or performance enhancement. The advent of VR has further transformed neurorehabilitation, offering an immersive environment that significantly enhances the rehabilitation process when coupled with MI. Studies highlight the efficacy of VR-based MI systems in post-stroke rehabilitation, demonstrating improvements in muscle strength and involvement degree. Beyond stroke, individuals with Parkinson's disease have seen notable enhancements in balance, motor function, and daily activities through combined VR and MI interventions. The integration of BCI with these techniques opens new possibilities, with P300-based BCI VR games showcasing the capacity to boost cognitive functions. This suggests that the fusion of BCI, VR, AO, and MI could pave the way for comprehensive rehabilitation programs, addressing both motor and cognitive domains. In essence, the amalgamation of AO, MI, VR, and BCI heralds a new era in neurorehabilitation and motor learning, offering an optimistic outlook for more effectively harnessing neuroplasticity and enhancing the quality of life for individuals with neurological challenges and beyond.

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