Neural Applications Using Immersive Virtual Reality: A Review on EEG Studies

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***Abstract*—Recent advancements in immersive virtual reality head-mounted displays allowed users to better engage with simulated graphical environments. Having the screen egocentrically stabilized in a way such that the users may freely rotate their heads to observe virtual surroundings, head-mounted displays present virtual scenarios with rich immersion. With such an enhanced degree of freedom, immersive virtual reality displays have also been integrated with electroencephalograms, which make it possible to study and utilize brain signals non-invasively, to analyze and apply their capabilities. In this review, we introduce recent progress that utilized immersive head-mounted displays along with electroencephalograms across various fields, focusing on the purposes and experimental designs of their studies. The paper also highlights the effects of using immersive virtual reality discovered through the electroencephalogram analysis and discusses existing limitations, current trends as well as future research opportunities that may hopefully act as a useful source of information for further improvement of electroencephalogram-based immersive virtual reality applications.**

***Index Terms*—Immersive virtual reality (VR), neural analysis, electroencephalogram (EEG), head-mounted displays.**

I. INTRODUCTION

IMMERSIVE virtual reality (VR) has been gaining attention after an explosive growth of VR technologies over the past decade. The key to such success is attributed to realistic immersive settings that VR head-mounted displays could produce and provide to users. VR head-mounted displays display the scene in first-person view, showing slightly different two-dimensional pictures to each eye to give the illusion that it is a three-dimensional environment that they are looking at [1], [2]. On top of that, precise head tracking allows VR head-mounted displays to make the scene the users are viewing look more realistic, contributing to creating more immersive settings [3], [4]. More importantly, low-cost conventional VR head-mounted displays with high-resolution frames are more readily available to the public, supporting the widespread use of such systems throughout various fields of interest. While VR head-mounted displays are generally used for entertainment purposes, their applications stretch beyond entertainment.

The capability of VR head-mounted displays in creating immersive settings with a high degree of freedom with minimal cost facilitates experiments, especially those that are associated with exploring and utilizing mental states of users. Observing brain signals is often regarded as a useful method when examining the mental state of the user, for it may also reveal what cannot be known through behavioral observation. Among various methods of acquiring information about brain activity, electroencephalogram (EEG) is widely used to fulfill the aforementioned purpose, providing brain signals in real-time by non-invasively placing electrodes on the scalp. The addition of VR is thought to provide further assistance in detecting and differentiating brain patterns by providing a realistic virtual environment. When Tian et al. used an immersive VR environment along with EEG to compare how emotion-related EEG evoked in 2D and 3D environments differ, they observed that emotional arousal was greater when emotional stimulation was given in the 3D environment [5]. Accordingly, the use of a VR environment in an EEG study offers the possibility of more effective observation of the user's response than traditional approaches that use a 2D screen to display an environment.

Findings that VR can be a useful tool in detecting neural patterns have justified the expanded use of VR head-mounted displays in EEG studies. Rehabilitation is one field that could benefit from the use of immersive VR environments and EEG. Oftentimes, the objective of rehabilitation is to promote movement-related neural activation to ultimately restore motor functions. When the users are immersed in a realistic virtual

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environment, the targeted neural activation is more easily induced, thus assisting the process of EEG-based rehabilitation. This is supported in numerous studies where immersive VR systems were used with EEG while performing imagination of different body movements [6], [7], [8]. Conversely, immersive VR environments can also benefit through the employment of EEG-based BCIs. One example of BCI adding functionality to VR is a menu navigation system designed by Armengol-Urpi et al. which utilized steady-state visually evoked potentials (SSVEP) through a VR head-mounted display [9]. Their system allowed intuitive hands-free control of a menu navigator and showed how EEG-based BCI can be utilized to enrich the VR experience.

Finding an optimal way of using VR in EEG studies is still an ongoing process. Whether its main focus is EEG-based rehabilitation, control, or examination, numerous attempts to find methods more advanced than traditional approaches using VR have been and still are being made. The paper intends to present a comprehensive review of EEG studies that utilize immersive VR and discuss how and for which purposes it could be used. Descriptions will touch on how VR is being adopted in EEG-based rehabilitation and control to improve performance as well as its uses in observing and analyzing the EEG signals of the users in a variety of settings. We aspire to provide insights on immersive VR-based neural systems through our contributions and have them serve as guidance for future research topics.

In this review, we used Google Scholar and IEEE Xplore to obtain works relevant to our topic. The terms for our search utilized combinations of keywords (“electroencephalogram” OR “EEG”), (“immersive virtual reality” OR “VR”), (“VR headset”), (“head-mounted display” OR “HMD”), and (“brain-computer interface” OR “BCI”). The studies retrieved from the search results were assessed prior to being included in our review. Studies that did not include the use of VR head-mounted displays were not considered in this paper unless they are associated with the theoretical background.

II. IMMERSIVE VR AND EEG FOR REHABILITATION

A major benefit of immersive VR is its ability to present scenarios different from real life with high degrees of immersion and freedom, which makes the presented scenario more realistic. Having the ability to inspect cortical activation of users, EEG combined with immersive VR has been brought to attention especially in the field of rehabilitation. For patients who are unable to move their specific body parts, immersive VR may be used to provide graphical body movement from a first-person perspective, replacing their affected body parts. Such an advantage may be a useful tool specifically in terms of stroke rehabilitation, where motor imagery, the mental practice of body movement without direct action, is trained in patients to improve their neural activity. With recent immersive VR techniques that provide realistic visualization, rehabilitative applications attempted to integrate immersive VR displays with EEG as well as other various types of biosignals and feedback such as those shown in Figure 1, to provide enhanced support for motor imagery and to measure and explore their effects on neural activation. Thus in this section, recently proposed rehabilitation systems based on immersive VR and EEG were reviewed to explore their progress and ideas.

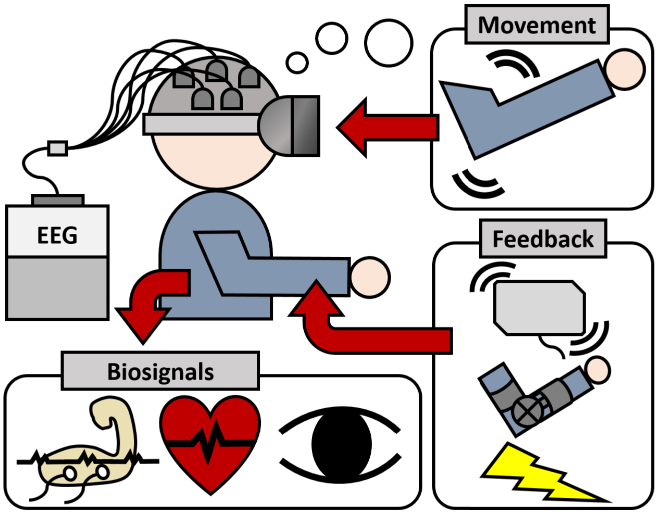

Fig. 1. Possible components for immersive VR-based rehabilitation systems. The system may include other types of biosignals such as EMG, ECG, EOG or eye tracking, and may also provide various feedback such as vibrotactile, proprioceptive, electrotactile, and FES in addition to visual feedback through the immersive VR display.

A. Rehabilitative Applications Combining Neural Signals and Immersive VR

Rehabilitative applications focus on inducing brain plasticity by having users activate related neurons [10]. Action observation, in which users were asked to observe body movements corresponding to the target brain region, is often applied in previous studies to have users enhance their brain signals [11], [12]. Presenting visualizations corresponding to specific actions is based on theories related to the mirror neuron system, in which neurons become activated by imitating and understanding observed actions [13].

Research that utilizes immersive VR tends to take advantage of enhanced embodiment, a feeling of a presented graphic body being the observer’s own, which is known to be effective for motor imagery [14], [15]. By showing immersive visualization of graphical body movement through a first-person perspective, immersive VR-based rehabilitative applications tend to improve corresponding neural activity. One of the rehabilitative methods that directly utilizes such an aspect is by combining action observation with motor imagery, in which users are led to think as if they are the ones performing the movement as they observe graphical actions from a first-person point of view. While it has been investigated in previous studies that action observation may be an effective method for neural activation, utilizing such an aspect along with semi-immersive and immersive VR displays has seen further neural activity enhancements compared to non-immersive displays [6], [7]. The body movements used for action observation do not represent motor imagery state of users. As the purpose of the visualization in action observation is to support the activation of mirror neurons by showing ideal movements that users should imagine, the presented bodily movements do not reflect any of the user's status, providing no information regarding the user's neural activity during training.

In contrast to action observation, feedback utilizes visualized movement to reflect user's motor imagery status by considering their brain signals. Thus for feedback, virtual actions corresponding to the classified intention from the user are reproduced, providing users an insight into their motor imagery performance. For instance, virtual body movement such as extension or flexion of a virtual arm [8], [16] may be presented according to motor imagery classification results based on the user's brain signals. With visualization being the main component for using immersive VR displays, other types of feedback are additionally used in motor imagery-based rehabilitation systems in order to have users remain focused throughout repeated trials and to better support users' rehabilitation experience. For instance, vibrotactile feedback was given with visual feedback from NeuRow where users are to imagine left and right arm rowing motor imagery [17]. Providing actual movement with proprioceptive feedback corresponding to visualization of arm flexion or extension is also possible using soft robotics [18]. Electrotactile stimulation feedback was also utilized with visual feedback for hand grasping, flexion, and extension motor imagery [19]. Functional electrical stimulation (FES) and haptic feedback are used with immersive VR as well. For instance, Lupu et al. proposed a TRAVEE system, where users may perform hand rehabilitation with a virtual therapist while electrooculogram (EOG), electromyogram (EMG), eye tracking, and EEG signals are recorded, and are designed to provide various feedback types such as FES, haptic, or robot assistance [20], [21]. Although feedback based on classification results of user's intent may confuse the users if the intents are misclassified [22], various feedback types were used along with immersive VR environments to maintain user attention through interactive scenarios and to support better cortical activation.

Putting the focus more directly on recovery, some applications also instruct users to attempt to perform the desired movements. For instance, Vourvopoulos et al. introduced a motor priming system along with a head-mounted display and gesture interaction device, where the EEG signal data of users were gathered while they were rotating the virtual lever by performing circular motor execution of the left or right arm [23]. The experiment with nine healthy participants showed that presenting such realistic feedback scenes through immersive VR was more effective for sensorimotor activation compared to the standard bar feedback, and motor priming had the potential for more engagement of neural circuits [24]. Spicer et al. implemented REINVENT, a neurofeedback system containing a head-mounted display, EEG and EMG sensors, and inertial measurement units (IMUs) attached to the palm and forearm. The system aimed for neuromuscular-based training usage, providing neurofeedback when users were to attempt movement even without its full execution [25]. The system was used in a scenario where users were instructed to move the virtual arm toward a ball by thinking about the corresponding movement [26]. With the advantage of immersive virtual displays having the ability to present 3-dimensional virtual scenes within the first person's perspective, previous rehabilitation systems utilized such a component with various other feedback and neural signals to provide support for users.

B. Patient Involved Rehabilitation and Clinical Studies

While much of the aforementioned immersive VR-based neural rehabilitation systems investigated their effect on healthy participants, relatively fewer works were conducted on actual patients with disabilities. Although a smaller number of works were conducted as clinical trials, some positive effects of immersive VR-based EEG systems have been reported. NeuRow, a system that utilized a rowing game scene and vibrotactile feedback, was used to train left and right motor imagery on a male patient with a chronic stroke [27]. According to the study, the patient's resting state EEG alpha band modulation increased from pre- to post-intervention, suggesting the possibility of motor recovery. Furthermore, the study claimed that the distribution of the patient's EEG data after the intervention was closer to those of healthy participants from their previous study [17]. Work from Moldoveanu et al. used the TRAVEE system to perform clinical trials on multiple stroke patients and explored the validity of the system [28]. According to the study, there were some cases where patients could see positive effects from the system. For instance, a patient with a very strong tremor in the arm, which restricted him from performing movements, could greatly reduce its size by performing repeated forearm flexion and extension movements guided by the virtual therapist of the system. Positive results were also seen in other patients through repeated exercises including palm and finger flexion-extension movements, which were visually augmented through the system. Using various feedback and visual representations of intended movements, the system sought to provide continuous and realistic feedback to give enhanced illusions to users [29].

REINVENT was also experimented on patients. In one study, a stroke participant was instructed to make an attempt to move a virtual limb controlled with neural signals towards a ball moving either the left or right side of the table [30]. The patient exhibited up to 95% success rate for controlling the virtual limb with the brain signals of the affected side, and the patient managed to improve performance during the latter half sessions compared to the former half sessions. Another study used EEG and EMG from REINVENT on four chronic stroke patients, claiming that patients with more severe motor impairments could benefit more from the EEG-based feedback while mild impairment patients could benefit more from the EMG-based feedback [31]. According to the study, all patients, regardless of their motor disability ranges, were able to safely use the system over repeated sessions. Work from Osumi et al. also assessed their immersive VR-based system with EEG recordings on patients with phantom limb pain [32]. In this experiment, two patients were instructed to move a virtual phantom limb, a symmetrical display of the patient's intact arm, towards a specific target. The study observed an alleviation of phantom limb pain and an increase in EEG alpha wave coherence where vibrotactile feedback was

TABLE I
IMMERSIVE VR AND EEG-BASED REHABILITATION SYSTEMS AND ITS APPLICATIONS

System/Design	Methods or Feedback	Presented Movement	Experimented Participant(s)	Scenario
Choi *et al.* [7]	Action observation	Hand grasping	Participants with no neurological disease	Participants were instructed to perform motor imagery while observing repeated left and right virtual hand grasping movements
Achanccaray *et al.* [16]	Visual feedback reflecting EEG signals [16] and with gazing [8]	Arm extension/flexion	Healthy participants, with one mobility impaired (amputated arm) participant involved	Participants were instructed to control extension/flexion of the virtual arm by performing corresponding motor imagery
Vourvopoulos *et al.* [17]	Visual, auditory and vibrotactile feedback reflecting EEG signals	Hand movement	Healthy participants [17] and a stroke patient [27]	Participants were informed to perform left or right hand rowing motor imagery to exhibit a boat's movement depending on the cue
Wairagkar *et al.* [18]	Visual and proprioceptive soft robotic movement feedback reflecting EEG signals	Arm flexion/extension	Healthy participants	Participants elicited intentions of an arm movement, resulting in a virtual avatar arm movement and a soft robot supporting the execution of the corresponding arm movement of participants
Achanccaray *et al.* [19]	Visual and electrotactile stimulation feedback reflecting EEG signals	Hand movement (grasping, flexion/extension)	Able-bodied participants	Participants were to perform ball grasping motor imagery previously shown from the animated cue, and the related feedback with stimulation presented after motor imagery
Lupu *et al.* [20]	Visual with FES, haptic, or robotic-assisted feedback reflecting EEG, EMG and EOG signals	Forearm, finger, thumb, arm, and shoulder movements	Patients with varying disabilities ranging from slight tremor to no motor control [28]	Participants were to perform instructions given by the virtual therapist, which varied depending on their status
Vourvopoulos *et al.* [23]	Visual feedback reflecting EEG signals or motor execution of participants	Arm and hand movement	Participants with no neurological disorder [24]	Participants were to execute or imagine rotating either a left or right virtual handle with the corresponding virtual hand to open a garage door
Spicer *et al.* [25]	Visual feedback reflecting EEG and EMG signals and IMU sensors	Limb movement	Healthy participants [26], Stroke patients [30], [31]	Participants were instructed to move a virtual limb towards a ball, which was moving to either the left or right side of the table
Osumi *et al.* [32]	Visual feedback showing the symmetric movement of an intact limb, and vibrotactile feedback depending on the completion of task	Limb movement	Patients with phantom limb pain	Participants were to move the virtual phantom limb, a mirror-reversed visualization of their intact limb, towards the randomly placed target object

presented on the impaired side's shoulder and cheek when the virtual phantom arm reached the target.

Immersive VR display devices have been used as an effective tool for rehabilitation and clinical studies due to their capability of creating and presenting scenarios that cannot be shown in real-life situations. Displaying natural movements of a virtual arm of a patient who is unable to move his or her arm is one example that shows such a capability of immersive VR displays. With the enhancement of embodiment being a major component, immersive VR has shown promising results with regard to inducing neural activity not only in healthy participants but also in patients, as summarized in Table I. Furthermore, VR displays can help users remain focused by blocking the view of the surroundings. An experiment that uses vibrotactile feedback and an EMG sensor, for instance, cannot completely exclude the possibility of distraction due to the presence of these devices, which could draw participants' attention. However, with a VR head-mounted display blocking sight to the outside world, it is safe to assume that the use of additional devices will not cause visual interference. With various types of feedback and biosignals added to support rehabilitation, studies using immersive VR-based rehabilitation systems attempted to further enhance the rehabilitation experience without visual interference while presenting targeted bodily movements in order to improve correlated neural activation of users.

III. BCIs INTEGRATED WITH IMMERSIVE VR

As an assistive interface for users with motor disabilities, BCIs provide hand-free control over the device by translating the user's intentions into device commands based on their brain patterns, as shown in Figure 2. To train and have users adapt to BCIs, immersive VR systems are often used to present real-life scenarios or provide scenes that may better engage users. Immersive VR systems are also combined with BCIs in research that attempts to offer more intuitive or direct interaction with virtual scenes. In this section, we explored current VR applications that use BCIs and categorize them into two types: reactive and active. This section will cover how each type of control interface took advantage of immersive VR.

A. Reactive Brain-Computer Interfaces for Immersive VR

A reactive BCI derives the user's intention from brain signals that are reactively generated by an external stimulus. The system is designed in a way that exposes the users to different stimuli according to the user's intention. Due to the nature of reactive BCI that requires an external stimulus, there is a wide range of design choices that come from the various ways of presenting external stimuli in a reactive BCI. Here, we focused on P300 and SSVEP-based controls using VR environments, which are two of the most well-known reactive BCI paradigms.

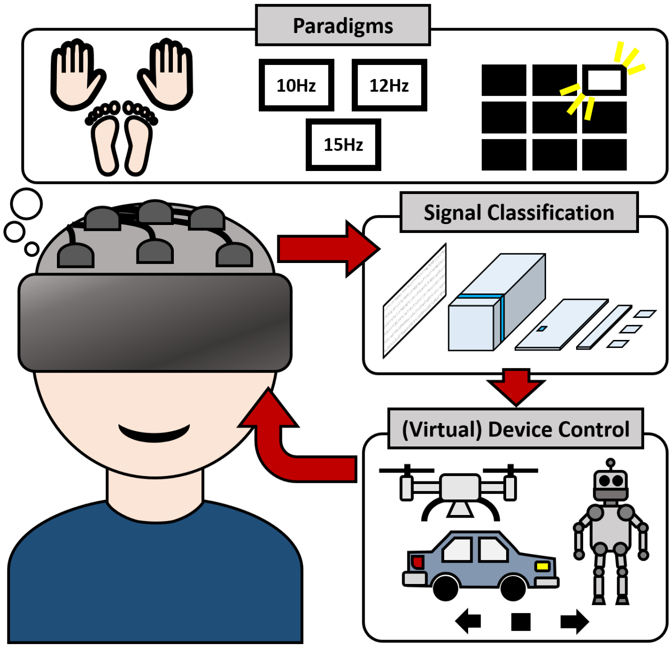

Fig. 2. Immersive VR-based BCI design choices. Different paradigms can be used by the neural system to produce discriminant brain patterns for classifying users' intentions, classification models to extract brain pattern features and translate them into device commands, and virtual or real-life devices to be controlled by users.

The P300 signals, an event-related potential (ERP) response that appears at about 300 ms after rare events, are often employed in reactive BCIs. Control interfaces using P300 come in different forms and serve different purposes. P300 control using immersive VR may be employed in drone control [33], a painting system [34], a speller [35], and even in a game [36]. Visual information to the user in P300 control is generally given by displaying command stimuli on a virtual plane floating in the VR environment [33]. Using P300 in VR environments does not seem to be a problem, as it is known that the system that presents a P300 stimulus through the VR display does not underperform the traditional approach which uses a 2D screen [37]. In fact, the VR environment allows the user to feel more present without affecting their cognitive workload [34]. It has also been claimed that presenting P300 stimuli through VR display did not have a negative impact on the control capability of a user with amyotrophic lateral sclerosis [35]. Users with spinal cord injury that may exhibit exaggerated neural responses when exposed to the stimulus [38] were also reported to show good levels of performance in an immersive P300-based BCI application [36]. In light of these works, there seems to be no issue in implementing P300 for VR environments.

SSVEP, which is induced by a target constantly flickering at a fixed frequency, has also been used in reactive BCI implemented in VR environments. It is widely used for its high classification accuracy, which allows for reliable control. The majority of reactive BCIs that involve SSVEP and VR intends to control the movement of an object or the player in VR. Multiple works that proposed an SSVEP-based BCI system that controls two-dimensional movement have seen improvements in information transfer rate (ITR). Works that improved ITR through the use of VR normally showed the first-person view of a device being controlled using a head-mounted display [39], [40]. This method, combined with SSVEP BCI, can provide users with a highly immersive experience while utilizing a reliable control method [41]. The system that showed an object from a third-person point of view also improved ITR as well with VR compared to using the monitor [42]. Meanwhile, the feasibility of a VR-based SSVEP control system is also present in controlling a 3-dimensional movement in a physical environment, as demonstrated in the work by Wang et al. [43]. SSVEP can also serve as a tool that enables the hands-free control of VR through BCI. Speller is one example that could assist the use of VR. The SSVEP-based speller implemented in VR enables the majority of users to convey words they intend to generate [44], and it has been explored that the SSVEP-based speller in VR can further raise its ITR with the help of EOG signals [45]. An SSVEP-based menu navigator can also allow the hands-free control of VR by making selectable objects in VR function as flickering boxes [9].

B. Active Brain-Computer Interfaces for Immersive VR

An active BCI extracts and translates features from brain signals generated intentionally by the user. Among various paradigms of active BCI, motor imagery is often used as a control method. While it may be paired with VR to control devices unrelated to body movements [46], a large number of motor imagery-based BCI implemented in immersive VR environments tend to control a virtual avatar. One reason is that the first-person view provided by the VR head-mounted display may be utilized to its full potential when displaying visual feedback by delivering an immersive experience to every participant, as such settings may give them a sense of ownership [47]. A number of studies focused on improving motor imagery-related neural activation by modifying the training session, which acts as a pre-requisite for using motor imagery-based BCIs for decent control. For instance, a display may show the left and right hands of a virtual avatar when it is controlled by left and right hand motor imagery, where each hand moves based on motor imagery classification results, to improve the MI-BCI skills [48], [49].

A lot of creativity has been involved to further improve motor imagery performance through visual feedback. Škola and Liarokapis visualized hand motions according to motor imagery classification results in the training phase, resulting in a higher average accuracy in motor imagery-based BCI control than when trained with a standard Graz training protocol [48], [50]. Making a motor imagery training protocol in the form of a VR game led to enhanced right/left hand motor imagery classification performance using the aforementioned principle while low fatigue levels were observed during the training [49]. The use of embodiment for higher motor imagery classification accuracy is not confined to discriminating EEG of right and left hand motor imagery. Showing the movement of a virtual avatar in the first-person view can show a trend for better performance with gait motor imagery as it did with right/left hand motor imagery [51]. Moreover, presenting visual feedback that reflects the correct movement of the leg regardless of the gait motor imagery classification results of the participants in the training process can lead to more accurate control of a virtual lower limb [52]. Although the majority of motor imagery-based BCIs implemented in immersive VR environments are designed to control the virtual body which corresponds to the body part moved in imagination, one can also effectively control an object unrelated to the human body through motor imagery-based BCIs. In fact, Choi et al. suggested that placing virtual hands and adding motions to them can give the sense of embodiment, which likely played a role in improving motor imagery-based control performance of a quadcopter [53].

Table II summarizes different paradigms and scenarios used for controlling either virtual or physical components through EEG signals. With either reactive or active paradigms, BCIs have been applied to various situations driven through the immersive environment and have seen their potential for usage with head-mounted displays. These studies reveal that using BCIs within immersive environments may be applicable in a variety of scenarios as much as using BCIs in real-life situations.

IV. Other Use Cases of Combining Immersive VR and EEG Acquisition

Recent studies employed EEG and VR head-mounted displays to explore various neural correlates during immersively driven circumstances or tasks, investigating the advantages and disadvantages of VR systems for their various potential usages such as for BCIs, clinical trials, and rehabilitation. To convey such appliances from numerous fields or interests, we handled 63 research articles in this section that utilized immersive VR combined with EEG. As can be seen in Figure 3, a diverse range of brain responses regarding specific tasks or circumstances was observed, and their approaches for investigating the cause of such neural responses also varied. In this section, we divided the articles into two different groups based on their experimental design: works with active experiments which involve tasks that may require active participation from the user such as bodily actions or mental practices, and studies with passive experiments where participants were exposed to a presented virtual environment without active tasks. The section focuses on the experimental designs and findings that may arise in specific circumstances, which may be considered for various immersive VR-based neural applications in the near future.

A. Simulations Involved With Active Participation

Oftentimes, it is beneficial for users to stay immersed in the given scenario when they conduct tasks that need active participation. Immersive VR systems, which are known to enhance the feeling of oneself being in the presented environment known as the sense of presence, are often employed to have users be engaged throughout such given tasks [54]. By comparing various tasks performed in both immersive and non-immersive displays, previous studies reported that performing tasks in immersive VR displays can lead to a higher level of concentration than non-immersive displays when given the same scenario [55], [56]. With such an advantage, graphically simulated tasks have been employed to explore cognitive states including workload, emotions, stress, and concentration, using simulated scenarios such as searching for a target shape from a visual array containing various distractor shapes [57], targeting a fired cannonball [58], conducting a Stroop test determining whether the text and its color were the same [59], [60], and playing an adventure game which involves exploration and problem solving [61]. Various scenarios from a variety of fields were studied along with the analysis of the user's neural responses to investigate whether immersive VR environments could be effective for tasks requiring active engagement.

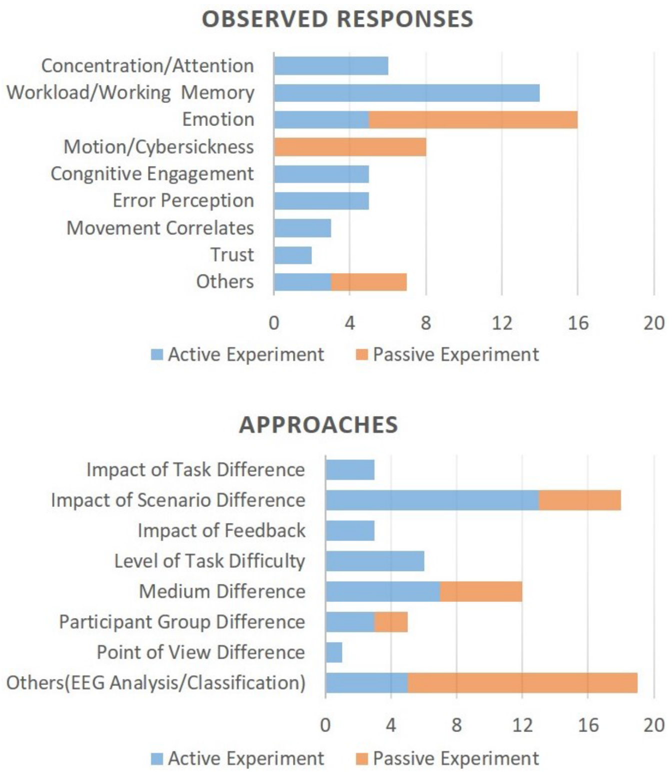

Fig. 3. The distribution of the number of literature reviewed in Section IV of the study. The upper figure represents the distribution related to observed brain responses, and the lower figure shows the distribution related to experimental approaches. Notice that a single article may be included in multiple categories shown in the figure.

Immersive VR systems were brought to attention in terms of cognitive thinking and learning, as the realistic graphical visualizations and immersion offered by these systems may provide a better environment for working and learning. Tasks related to work efficiency and cognitive performance [60], [62], concentration and creativity [63], or knowledge retention and cognitive engagement [64], [65] were performed within different virtual settings. While many studies have investigated learning in immersive environments, it is still unclear whether they are effective. A work from Baceviciute et al. compared the learning performance of participants when they were reading a virtual book in a virtual hospital setting versus when they read a real book in the real world [66]. The results showed that reading a book through immersive VR had significantly better knowledge transfer, and was associated

TABLE II
Immersive VR-Based BCI Systems

Study	Paradigm	Number of Commands	Findings	Scenario
Kim *et al.* [33]	P300	7 (direction buttons)	Confirmed that P300 is stable in VR environment	Participants were asked to move the drone according to the instructions provided in both an AR and VR environment
McClinton *et al.* [34]	P300	36 (painting utility, i.e. cursor movement, switching color or brushes)	Users felt more present when using the application in an immersive setting	Participants performed a painting task using a proposed painting interface in both a VR and non-VR environment
Käthner *et al.* [35]	P300	25 (alphabets excluding the letter z)	Healthy users achieved spelling accuracies of 96% with VR display as high as the approach that uses the monitor (94%)	Participants completed a spelling task using a monitor and two different interface designs using VR
Tidoni *et al.* [36]	P300	9 (each token with an assigned value between 1 and 9)	Both healthy participants and those with spinal cord injury showed good performance when using BCI in the immersive scenarios	Participants, both healthy and those with spinal cord injury were asked to play a P300 cooperative game in a VR environment
Stawicki *et al.* [39]	SSVEP	3 (turn left/forward/turn right)	VR setup required a lower number of movements to finish the task and yielded higher classification accuracy	Participants were asked to finish a maze game twice using SSVEP, each with VR and laptop screen as a display
Stawicki *et al.* [40]	SSVEP	3 (turn left/forward/turn right)	Using VR yielded a higher ITR and reduced the total time spent to complete the task than the monitor	Participants were asked to play a game where the aim is to clean 10 dust mounds with a virtual robotic vacuum cleaner using VR and a desktop
Stawicki *et al.* [41]	SSVEP	3 (left/forward/right)	High average accuracy (98.1%) achieved in the study backs up the reliability of the system	Participants were asked to steer the mobile robotic car through a given course using VR-based SSVEP-BCI
Koo *et al.* [42]	SSVEP	4 (each direction that a player can take in the maze)	Playtime was reduced and ITR increased when using VR head-mounted display (playtime 34.19 seconds, ITR 24.58 bits/min) than when using the monitor (playtime 37.99 seconds, ITR 22.17 bits/min)	Participants were asked to finish a maze game with a monitor and VR head-mounted display
Wang *et al.* [43]	SSVEP	4 (up/down/forward/right)	The proposed VR-based system with an asynchronous switch approach allows the user to accomplish 3-D flight task smoothly and accurately	Participants were asked to gaze at the stimulus of a particular direction according to the random auditory cue and performed an online test along with it in the first experiment and to lead the drone to the luminous target in the second experiment
Grichnik *et al.* [44]	SSVEP	3 (3 steps of three choices SSVEP)	Achieved an average accuracy of 91.11% with 23.56 ITR	Participants were asked to perform 7 different spelling tasks using the proposed system
Ha *et al.* [45]	SSVEP	9 (in a 3 × 3 grid, column classified by EOG and the row classified by SSVEP)	Using SSVEP with EOG yielded higher accuracy (average accuracy 97.74%) than when using SSVEP only	Participants performed a proposed system in three different configurations, having different frequencies for each stimulus
Armengol-Urpi *et al.* [9]	SSVEP	4 (4 different movies in the main menu)	Participants achieved lower ITR than the conventional SSVEP BCI, but achieved 100% accuracy and felt more comfortable using the proposed system	Participants performed a predefined navigation task using the different amplitude of luminance functions of the application icons and had a chance to interact freely to answer a survey
Coogan and He [46]	Motor imagery	4 (left/right/up/down)	Suggested that EEG can be carried into various reactive and active BCI applications using widely available software packages	The first study evaluated the performance of users with and without experience of SMR-based BCI in a cursor control within VR and non-VR environments and the second assessed the learning rates between traditional and the VR-based approach
Alanis-Espinosa and Gutiérrez [47]	Motor imagery	4 (classifications using left/right/both hands and both feet)	Analyzed functional brain connectivity using immersive control of a robot	Participants controlled a robot in a third person point of view and using a head-mounted device in a first-person view
Škola and Liarokapis [48]	Motor imagery	2 (left/right hand movement)	The group trained using embodied VR environment achieved 58.3% motor imagery accuracy while those that used a standard bar protocol achieved 52.9%	A classifier was trained gradually, giving visual feedback of pressing a button through the hands of a virtual avatar differently in each step
Škola *et al.* [49]	Motor imagery	2 (left/right hand movement)	The average peak accuracy of 75.84% shows that the proposed training method improves the motor imagery performance	Participants performed six runs in training, the first run involved motor observation in VR, in the second to fifth received real-time feedback based on the user's EEG signals, and in the last received post-trial feedback of shooting a weapon from either the left or right side of a spaceship
Ferrero *et al.* [51]	Motor imagery	2 (gait movement, relax)	Experiments showed a satisfactory result of 91.0% accuracy of issued commands	Participants trained motor imagery using both the VR and screen while standing or seated with visual feedback of moving themselves through the corridor, and participated in an online session using a trained classifier
Alchalabi *et al.* [52]	Motor imagery	3 (left/right step, no movement), 2 (walking forward, no movement)	Introduced the BCI of a lower limb using different control modes and commands, and the performance increased through positive modified feedback	After gradually training two classifiers over the course of three days, two groups of participants received different feedbacks on the third day, and were then instructed to control self-paced lower limb motor imagery in two randomly presented modalities on the fourth day
Choi *et al.* [53]	Motor imagery	3 (left rotation, right rotation, forward movement)	Presenting embodiment over a motor imagery-controlled device may improve control performance	Participants were asked to control a virtual device to the destination both with and without virtual hand feedback resulted from their EEG signals

with higher theta and lower alpha and beta EEG activation indicating a demand of greater cognitive engagement in the immersive VR environment. Kalantari et al. performed experiments using numerous cognitive tests in both a real-world classroom and an identical immersive virtual classroom while measuring biosignals including EEG. No significant differences in the accuracy of cognitive tests were exhibited as well as EEG band-power, except for the frontal lobe during the Benton test [67]. Makransky et al. utilized a virtual science lab in a learning task that learns mammalian transient protein expression and simulated it for participants using either a desktop display or a head-mounted display [68]. The work showed that using the head-mounted display felt more present but was to learn less while exhibiting a higher EEG cognitive workload compared to using the desktop display.

There were also comparisons of using different learning materials in different environments. Parong et al. conducted a learning experiment with students where they were asked to view a biology lesson either through immersive VR with interactive animated scenes or through a slideshow on a monitor screen [69]. The EEG results showed that higher engagement and more ideal cognitive workload were shown when viewing the slideshow through the monitor screen, whereas the lessons using immersive VR showed more cognitive distractions and less learning outcomes. In light of the aforementioned negative and positive results from immersive VR experiments, a variety of interpretations can be made regarding the possibility of immersive content supporting learning and cognitive thinking. Thus, investigations regarding such aspects may be conducted in-depth in order to further develop immersive content that would maximize its positive influences.

Unlike some questionable effects of immersive VR on the learning and cognitive thinking of healthy users, its effect on mental treatment and cognitive training on patients seems more promising. Several cognitive training methods such as P300-based social attention training for autism spectrum disorder (ASD) [70], cognitive training for attention deficit hyperactivity disorder (ADHD) [71], [72], and a gamified exercise protocol for patients with upper-extremity injuries [73] were proposed and investigated, exhibiting the effect of the systems on patients with repeated training. Furthermore, EEG signals retrieved during training may also be utilized for screening cognitive impairment [74]. To retain the concentrative state of participants and to have them maintain an immersive state throughout presented scenarios, immersive VR has been employed in various virtual circumstances.

The feasibility of neural signals as feedback for difficulty adjustment in immersive VR applications has also been researched, as there exist many circumstances where adjusting tasks depending on the mental state of users may provide positive effects or lead to a better outcome. Entertainment such as gaming applications, for example, providing possibly challenging tasks may relate to the excitement of users. Such a factor was considered in a work by Abdessalem and Frasson, which proposed an immersive VR game with EEG-based feedback where users were to control a virtual ambulance through obstacles, while biosignals including EEG were measured to calculate the frustration and excitement of participants to continuously adjust the difficulty of the game [75]. Task difficulty adjustments are also important for mental training applications, as the performance of users differs and providing tasks with optimal difficulty for the user may enhance the effect of overall training. For instance, Dey et al. introduced an adaptive training system with a target shape searching content, where the real-time measured EEG alpha wave was used to adaptively train participants with task complexity of 20 increasing levels [76]. These studies showed that significant impacts or relationships were found when the difficulty of the task was adjusted, providing potential usage of neural signals as feedback in such aspects. Considering that the level of the cognitive workload of users could be measured and analyzed using EEG signals [77], [78], [79], recent immersive VR applications attempted to apply EEG to adjust the difficulty of tasks for improving the user's entertainment or training experience.

There were also studies related to solving the current technological limitations of immersive VR systems by using EEG. One of the existing limitations of immersive VR systems includes sensory mismatch between the expected motion and their perceived outcome which may be sensed through visualization or haptic feedback. Through such unexpected outcomes caused by delays or other erroneous factors from the system, users may exhibit sensory mismatch causing users to feel that an erroneous response has occurred. Previous works could observe such mismatch feelings through a pattern known as prediction error negativity (PEN) from EEG [80], [81], [82] and could also discriminate such erroneous events using the recorded neural signals [83], [84]. Attempts to enhance image streamings within immersive VR displays were also held, where the idea is to predict the head rotation of users through EEG signals and may potentially be used to prepare for the images prior to the actual head rotation. [85], [86]

Several other simulations were conducted within immersive VR to see how varying conditions may affect their task performance. Scenarios involving possible circumstances that may occur in real life were explored through the immersive environment to present a better reality while users are performing the task. For instance, A study from Kalantari et al. held a wayfinding experiment in a virtual hospital facility to explore whether better architectural features and wayfinding signs with enhanced color may affect navigation performance [87]. Enhancement of color and architectural features could also improve the wayfinding performance of participants, with significantly greater neural processing from their occipital lobe. Affanni et al. employed an immersive driving simulator where participants were given three different driving conditions: a manual mode where users were to drive manually, gentle mode where the vehicle was driven autonomously and gently, aggressive mode where the vehicle was autonomously and aggressively driven [88]. The study claimed that stress-related EEG bata waves were higher in the manual mode compared to the two autonomous driving modes. There were other scenarios aiming to investigate neural activity in certain tasks, such as riding a reverse steering bicycle after visualized mental training of a normal bicycle or performing shape searching task with an agent providing auditory feedback with different accuracy rates, to explore the difference in neural activities of adaptors and non-adaptors [89] and to measure trust on the agent with the EEG signals [90], respectively. While many simulations with different tasks or environments were designed and experimented with EEG signals, previous studies tend to observe whether discriminant neural characteristics may be exhibited in specific situations, looking forward to applying such findings within various immersively presented scenarios in the near future.

B. Passively Involved Simulations Within Immersive VR

Not only does the immersive virtual environment facilitates the investigation of participants' cognition through active participation in certain tasks, but can also be used to analyze how EEG can be induced by simply observing a specifically designed environment. Numerous works that have attempted to do so involved immersive virtual environments to either analyze responses that accompany with the use of immersive virtual settings or to effectively induce targeted neural signals of the user.

Cybersickness is perhaps one of the most studied examples of the prior. One obstacle to using VR head-mounted displays is that cybersickness easily occurs with the use of a device. This matter must be resolved as it limits user playtime and hinders the development of VR industries. It is crucial to understand and detect cybersickness in order to prevent it in advance, but determining whether or not the user is experiencing cybersickness can be subjective and vague. One way to tackle this problem is through EEG where the neural signal of a VR user is monitored and classified to predict if the user is experiencing cybersickness. It has been suggested by previous studies that EEG can provide clues about cybersickness as theta and beta bands get elevated with visually induced motor sickness [91] and alpha and gamma bands can be used as valid indicators of motion sickness [92]. The conventional approach to collecting cybersickness-related data is to show various VR scenes that would induce cybersickness such as roller coaster riding experience [93], [94], [95], roaming around [96], a spaceport riding with intense movement [97], and etc. [98] to the participants while recording their EEG signals. The participants would subjectively mark the moment when cybersickness occurs while they observe the scene. The collected datasets are used to investigate the performance of a classifier that classifies cybersickness-related EEG. Using extra input such as video sequences [98], electrocardiogram, and galvanic skin response [95] on top of EEG has also seen success in classifying VR cybersickness occurrence of a user. EEG of people with multiple sclerosis experiencing cybersickness has been analyzed as cybersickness could impact the rehabilitation of multiple sclerosis patients that uses VR [99]. At this point, it seems evident that EEG can provide useful information about cybersickness and similar types of sickness as EEG exhibited when experiencing motion sickness, which is known to resemble cybersickness, has also been discriminated through the use of VR and motion simulator [100].

While studies about the sickness that commonly occurs with the use of VR environments utilized head-mounted displays to induce targeted responses, other works have shown that VR head-mounted displays can also be a prevailing tool that effectively generates neural signals related to emotional states from users participating in a passive activity. In most cases, such an effect was made possible by allowing the participants to feel more involved in the environment. Emotional arousal level is a popular measure used in EEG-based emotion recognition and was reported that arousal is associated with the alpha band of the frontal cortical regions [101], [102]. It has been shown that EEG recorded while observing scenes within immersive virtual 3D environments tend to exhibit more distinctive patterns related to arousal than when viewing with a 2D screen [5], [103]. Hence, studies that involve multiple VR scenes intend to effectively induce specific emotions through the use of VR head-mounted displays and have the subjects observe such scenes while recording their EEG signals. Recorded EEG signals are generally labeled based on self-assessed emotion and are used to measure the classifier's performance. Such an approach was used to construct valence and arousal-related EEG datasets and classify them [104], [105], [106], [107]. However, it is also important to note that conclusions may need to be made carefully when VR is used to evoke certain neural signals as EEG evoked from observing VR environment is clearly distinguishable from EEG evoked from observing in a physical environment [108], [109]. Studies that confirmed the anxiety-lowering effect of VR experience suggested that VR devices can be used not only to induce emotional state for the purpose of effective observation but also for anxiety management purposes as well [110], [111]. A study that monitored the emotional states of the passenger of an autonomous vehicle operated in a VR environment shows how emotion recognition through VR and EEG can potentially serve as practical methods in real life [112].

The expandability of VR environment designs extends the use of VR beyond simply evoking emotional responses. Various use of VR in observing distinctive EEG patterns include comparative analysis on smokers and nonsmokers [113], studying the neurophysiological mechanism of language processing in a realistic environment [114], and finding an optimal light condition that minimizes fatigue [115]. One can also add a visualizing effect through EEG feedback to provide a sense of unity among multiple VR players [116], or can even utilize it to diagnose epilepsy [117]. Although the function of each of the proposed systems may differ, they are all similar in the sense that the studies intended to provide realistic environments through the use of VR.

V. DISCUSSION AND FUTURE DIRECTIONS

VR head-mounted displays gained attention for their ability to display graphical scenes without viewpoint limitations and in a more realistic way. As a result of the immersion provided by VR displays, users may perceive their avatars within the scene as their own bodies and feel as being present within the simulated virtual environment [118], [119], [120]. The effects of VR are especially useful in constructing scenarios where users need to be deeply engaged in specifically designed situations. From the exploration of different brain patterns in various circumstances to applying such neural characteristics or findings to enhance interactions within virtual environments, immersive VR systems have been used widely along with EEG to track real-time brain signals of users.

When conducting various experiments involving immersive VR displays, one should consider that the brain signals induced while wearing the head-mounted display may not be identical to those generated when not wearing the head-mounted display, even under similar circumstances [121], [122]. Although there may not be an artifact directly from the medium that affects the retrieved signals greatly, there may still be artifacts from the line hum and the VR display's refresh rate [123]. Along the same line, confirming the effect of VR in inducing specific responses is essential. While it may be true that VR is capable of providing realistic environments, whether it efficiently induces targeted neural responses may require additional consideration of other influences such as neural responses related to immersion or visualization affecting the frontal, parietal, or occipital lobes, which may be irrelevant to the targeted neural responses [66], [124]. Thus, experiments that aim to explore how well the VR evokes responses in comparison to other scenarios or mediums should be aware that unexpected neural activities may also be exhibited due to passive influences from using the VR display itself.

As BCIs are used as assistive tools to support people with motor disabilities, VR environments are often used for entertainment or training users to adapt to the interface with safety. Several attempts to combine VR with BCI have shown promising results regardless of the paradigm used. The use of reactive BCI-based control systems in VR environments has shown notable improvements in multiple works, whether based on ITRs or accuracy tests. Nonetheless, one crucial issue with reactive BCIs such as SSVEP and P300 is that they cause fatigue in users [125], [126]. Although a previous study has shown that the users' performance when using reactive paradigms is not influenced by the difference of medium such as between VR and monitor display [37], such systems may not be adequate for long-term usage. On the other hand, active BCI-based systems, in which the majority utilize motor imagery, may take advantage of immersive VR systems with their sense of body ownership and embodiment. The fact that immersive environments can give users the sense of ownership and embodiment of a virtual avatar and offer them intuitive control methods may allow users to concentrate on the task and be immersed in the experience [127], [128], [129], [130], leading to enhanced control performance. Yet whether it can be used to control devices unrelated to body movement remains to be seen, and there are still a lot of experiments or comparisons regarding such a matter that needs to be done. Despite the fact that few explorations focusing on controlling a virtual avatar or utilizing virtual body movements as feedback have been made, further studies exploring the cognitive mechanisms or brain connectivity behind such aspects seem to be in need further.

Although a large portion of research utilizes EEG as a control interface for immersive VR systems, its future direction and purpose have not been clarified. Various virtual devices were controlled with different paradigms to explore the feasibility of using EEG for control within immersive environments; however, a more in-depth discussion should be conveyed to explore future directions for applying such technology outside of the lab environment. There have been previous attempts in some fields that showed the feasibility of using immersive systems with EEG such as for entertainment [58], [75], [116], clinical treatment and rehabilitation [7], [27], [71], [72], and also for controlling real-world devices [41], [47]. Among the most important aspects of BCIs in terms of control is their accuracy, which is a major concern for the feasibility of EEG-based neural systems. Brain signals vary not only between individuals but also within individuals depending on when with what medium and in what environment the system is used. While there are numerous studies underway to solve these problems by incorporating various machine learning and deep learning architectures to consider subject-dependent, subject-independent, and session-dependent aspects [131], [132], [133], [134], the accuracy of BCI performance requires further improvement for commercial applications.

There has been ongoing research, especially in the field of rehabilitation, which may possibly take huge advantage of immersive VR systems. With stroke rehabilitation based on mirror therapy [135], [136], recent studies tend to utilize immersive VR to provide virtual body parts with normal movement that may replace the affected body in reality. Immersive VR systems are also integrated with other feedback components and have had success in enhancing the engagement of patients, as well as using other biosignals to better analyze their intentions. The use of immersive VR systems has been seen as positive by many studies, but there are also some important issues to consider for its future. Due to the immersive VR system's bulkiness when used along with other devices such as EEG recordings [137], it acts as one of the hurdles for experiments especially for clinical treatments and rehabilitation which may take a considerable amount of time for training. Cybersickness may also be an obstacle that may restrain patients as well as other users from taking advantage of the system in a long-term manner [120], [138]. Even if VR head-mounted displays can help increase motor imagery performance or rehabilitation, there is no way to guarantee its practicality without resolving the cybersickness issue as this will prevent prolonged use of the device. As a result of such remaining issues, studies combining neural signals and immersive VR systems may encounter difficulties in recruiting participants, especially when the experiments involve patients. The development of further technical advancements that may improve the reliability of immersive VR and neural systems, as well as components that may prevent fatigue of users, should thus be considered for future research.

What has been left out as well is that there is still room for further comparative neural analysis between traditional approaches and immersive VR approaches. In terms of learning and education, for instance, whether or not to use immersive systems for retaining knowledge remains ambiguous. With different learning materials and from different circumstances providing different results in previous studies, more investigations that may further clear such aspects may provide better insight into immersive VR in terms of knowledge perception. Such comparative analysis should also be investigated in terms of clinical treatments such as for users with ADHD or ASD, narrowing the effect of immersive VR usage in terms of cortical activation.

VI. CONCLUSION

In this review, we provided insight into recent immersive VR-based neural systems that are utilized in various ways to exploit discriminant cortical activity within virtual settings. Increasing interest in immersive VR systems has led to the development of applications in various fields including entertainment, learning and education, rehabilitation, and clinical treatments. With the appliance of EEG, the advantages of immersive VR systems have been explored with a growing number of evidence from neural recordings. Here, we attempted to show recent progress and findings that were made from wide ranges: the analysis of neural activation in specified virtual situations to cases that applied such findings for systems, application, and interaction usages. Along with the summary of current literature covering combined usages of immersive VR and EEG systems, we presented some possible future works and current limitations of such aspects. We hope our work may provide a better understanding of immersive VR-based neural applications and would help bring more interest to such an emerging technology.

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