Chapter *X*:
Brain-computer interfaces for mediating interaction in virtual and augmented reality

Author(s):
[*]J. Faller (Columbia University, josef.faller@gmail.com)
N. Weiss (Columbia University, neilweiss1@gmail.com)
N. Waytowich (Columbia University / U.S Army Research Laboratory, nick.waytowich@gmail.com)
P. Sajda (Columbia University,psajda@columbia.edu)

9.1 Virtual and augmented reality (VR/AR)

Virtual and augmented reality (VR/AR) is an immersive and multimodal sensory experience that augments, or completely replaces, our regular, real-world sensory input with artificial content. Key to the VR/AR experience is the interaction between the human and the computer generated/augmented environment. VR/AR is not simply a display modality but an experiential modality that will potentially change the way we interact with virtual content and even our "real" world. The potential for VR/AR is so great that the last several years have seen dramatic increases in investment in the potential commercial applications of VR/AR, with major tech companies such as Google, Microsoft and Facebook having their own products and platforms.

In this chapter, we look at how VR/AR might be used together with recordings of brain activity, to better understand how we interact with the world. We describe how brain-computer interfaces (BCIs) are being integrated with VR/AR to rehabilitate and assist the injured and disabled, improve interaction between human and computer and provide us more insight into how our brains process and evaluate complex environments and events.

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[*] Corresponding author

9.1.1 What makes VR/AR interesting for research?

In any experiment, as scientists, we try to isolate variables so as to detect differences in these variables across conditions. This requires tight control of the environment, often at the cost of overly simplifying the experiment. On the other hand, in cognitive neuroscience we are interested in how our brains parse and interact with complex scenes and situations. This, of course, is best done if presented in a way that is similar to the real world (i.e. has ecological validity) so that we can generalize from the experiment to relevant real-life situations. These two goals – tight control of the environment, and authenticity to reality – are often at tension with one another.

In considering such a trade-off, VR allows for a high level of control while maintaining an immersive, naturalistic environment. This level of control facilitates acquisition and synchronization of experimental data, which is especially important for relating events in the environment to neurophysiological signals. The naturalistic environment is important for building a scientific understanding of how human perception, cognition and emotion operate in a complex environment.

AR can be viewed as a step in between the real world and virtual worlds, where real-world sensory input is overlaid with artificial stimuli, allowing the experimenter to leverage both ecological validity and tight control. Finally, another considerable advantage of VR and AR is that they allow one to realize experimental setups that might otherwise be infeasible, unethical, and/or too difficult or expensive.

Neurophysiological measures of interest in VR/AR are usually varied and differ in their temporal and spatial resolution. Compatible types of measures of brain activity include, but are not limited to, the electroencephalogram (EEG, Schomer & Da Silva, 2012), the electrocorticogram (ECoG, Moran 2010), functional magnetic resonance imaging (fMRI, Sitaram et al., 2008) or functional near infrared spectroscopy (fNIRS, Sitaram et al., 2007).

9.1.2 Measures of VR/AR fidelity: Immersion & presence

"Immersion" in the context of VR/AR, can be defined as the "extent and fidelity of sensory stimulation" and the responsiveness of the system to user action (Bohil et al., 2011). A more sophisticated sensory illusion, will have a higher level of immersion. A more immersive system in turn will give the user a stronger sense of presence, the "feeling of being there" (Biocca 1997). Presence can be defined more formally as "the perceptual illusion of nonmediation" (Lombard & Ditton 1997; Bohil et al., 2011). Presence is commonly quantified through self-reporting, for example through the Slater-Usoh-Steed questionnaire (Slater et al., 1994).

9.1.3 How VR/AR setups work

At a minimum, most VR/AR setups manipulate the input to the user's sense of vision. The least immersive technique is "desktop-based VR", where 3D objects are rendered to a 2D computer monitor (e.g. Scherer et al., 2012). This technique has the advantage of being the least expensive and simplest to implement. Some 2D monitors support the use of shutter-glasses or other techniques to create a 3D illusion by presenting an adjusted image for both the left and right eye (Marathe et al., 2008). 3D projection walls typically create a three-dimensional illusion in a similar way, but offer a larger field of view (Slobounov et al., 2014). Head mounted displays (HMDs) generally have a higher level of immersion. They are fixed to the user's head and present separately rendered images for each eye. HMDs track the movement of the user's head so that the images adapt to the orientation of the head (e.g. Faller et al., 2016; see also Figure 1, Panel (A)). At a similar, high level of immersion, CAVE audio visual experience automatic virtual environments (CAVE, Cruz-Neira et al.,1992; see also Figure 1, Panel (B)), position the user in a box, where images are projected onto each wall. Like with HMDs the images are dynamically rendered and take into account head orientation.

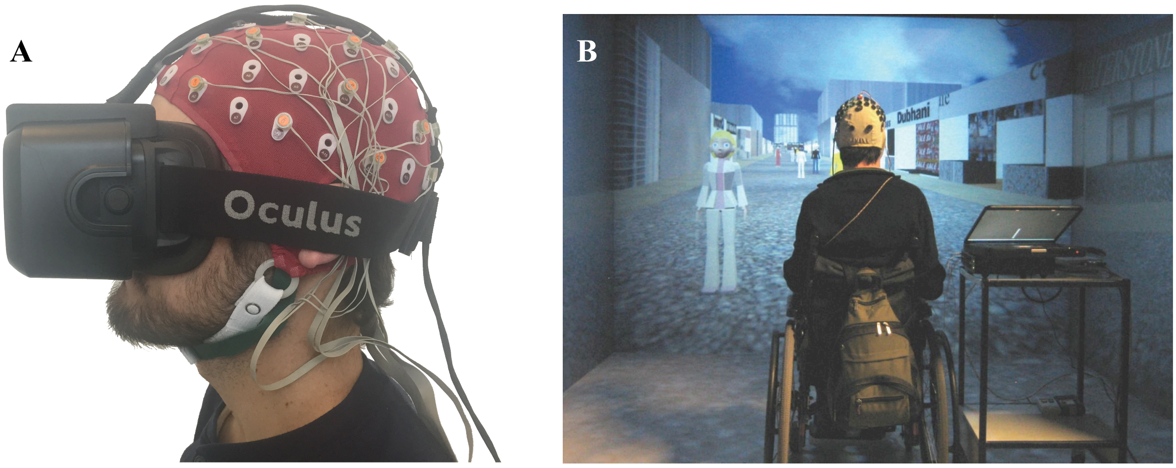

Figure 1: Panel (A) shows a healthy user wearing an EEG electrode cap and a head-mounted device (HMD). Panel (B) shows a disabled individual moving through an immersive CAVE environment only by imagining movement of the feet (Leeb et al., 2007).

Visual, auditory (Begault & Trejo 2000) and somatosensory (Lee et al., 2004) stimulation are often combined to create a more immersive experience, while other stimulation modalities like olfaction (Barfield & Danas 1996) or gustation (Narumi et al., 2011) have received less attention so far, especially in the context of BCI.

Similar to the fidelity of sensory stimulation, interactivity is another key component for creating highly immersive VR/AR systems. Non-naturalistic interfaces, such as a keyboard or a computer mouse, despite being easier to work with, are typically less immersive. Other interfaces, such as joysticks, wands, gloves that track finger movement (Bowman et al., 2002), head-, eye-, extremity- or body-trackers (Zhou et al., 2008) are more naturalistic forms of interaction that provide a higher sense of presence.

Brain-Computer Interfaces (BCIs), which decode brain activity for real-time communication and control (Wolpaw et al., 2012), are potentially the most naturalistic form of interaction with the VR/AR environment, as they aim to establish a direct link between the brain and system. From the perspective of the user, the nature of this interaction can be characterized in the following ways:

- **Conscious and spontaneous interaction: Active BCI** (Zander et al., 2011)

  Active BCIs rely on signals that are generated when the user actively modulates their brain-activity as the basis of control. For example, using movement imagery, cognitive tasks or other control strategies to modulate the sensorimotor rhythms (SMR).

- **Directing attention to external stimuli: Reactive BCI** (Zander et al., 2011)

  Reactive BCIs utilize brain signals that are elicited in response to external stimuli. In the oddball paradigm, for example, a set of stimuli (e.g. visual, auditory or tactile) is presented and the user pays attention to one stimulus that occurs less frequently. In the EEG this task causes a measurable positive deflection (P300) in evoked potentials (EP). This deflection can be measured and used for interaction through what is referred to as a P300-based BCI.

  As another example, stimulation in the range of 5 to 30 Hz causes a measureable modulation in brain activity, the steady-state evoked potential (SSEP). If the stimulation is visual, the signal is referred to as a steady-state visual evoked potential (SSVEP).

- **Subconscious, seamless interaction: Opportunistic BCI** (Saproo et al., 2016) or **Passive BCI** (Zander et al., 2011)

  Passive (or opportunistic) BCIs, passively monitor brain-activity for indirect control. Based on changes in brain-signals, such BCIs could, for example, track fatigue or other mental states, or detect when the user’s expectation is violated.

Another increasingly studied concept is that of Hybrid BCIs (Pfurtscheller et al., 2010). A

Hybrid BCI uses at least one CNS signal and at least one additional CNS or non-CNS signals, either sequentially or in parallel. The aim of combining a BCI signal with other signals is to improve information throughput and/or robustness of the interaction.

9.2 General research applications for virtual and augmented reality

Outside the context of BCI, VR has been used in basic research on spatial cognition and navigation, social sciences or multisensory integration like for investigating the phenomenon of the body-transfer illusion (Slater et al., 2010). VR has also been widely used in research on therapeutic applications like pain remediation, neurorehabilitation, and the treatment of psychiatric disorders, for instance treating anxiety through exposure therapy (Bohil et al., 2011). Finally, VR has been used where a virtual simulation of an environment, procedure, or scenario is more effective than standard instructional training, like for example simulations of procedures and surgeries for training medical personnel (e.g. Seymour et al., 2002).

AR has also been used for improving training effectiveness. For example, healthy individuals were made to show symptoms of specific ailments through the use of AR so that medical professionals could train in diagnosis and treatment (Ikeda et al., 2008). In military aviation, head-mounted displays have long been used to project critical information such as air speed, altitude, etc., into the field of view of pilots in fighter jets (Wood et al., 2016).

9.3 Virtual reality and brain-computer interfaces

Virtual Reality has been used extensively in the field of Brain-Computer Interfaces. VR provides a novel feedback modality for BCIs that allows for increased immersion and presence for direct-control BCIs as well as therapeutic intervention. This section gives an overview of notable contributions using virtual reality with brain-computer interfaces. Several VR-BCI based applications will be discussed such as VR-BCIs for direct-control and exploration, for augmented human-machine interaction, and for therapeutic intervention.

9.3.1 Control and exploration

BCI researchers have investigated numerous ways of incorporating VR into BCIs for direct control and exploration of a user's environment. Such work has primarily been applied to active, reactive and hybrid BCIs, with passive BCIs receiving much less attention so far.

There are numerous examples of virtual reality being applied to active BCIs, where users consciously modulate an endogenous signal that can be used to control a computer or peripheral device. The most commonly used modality for active BCI is the voluntary modulation of the sensorimotor rhythm (SMR). By increasing immersion and presence, VR has been used largely to give richer feedback, to thereby enhance subject's control of SMR signals. In one such example from 2003, Pineda and others sought to improve SMR BCI efficacy through VR-enhanced training of the participants (Pineda et al., 2003). The authors were able to show an increase in maximum mu rhythm amplitude after 10 hours of training sessions, in which subjects would control turning left and right through imagined movement of the hands in a 3D shooter presented in a desktop-based VR system. Over the next few years, Leeb and colleagues gradually increased the level of immersion to HMD-mediated VR and demonstrated that healthy subjects were able to turn left or right in immersive VR using a more challenging synchronized SMR BCI interface in which a user had to control the BCI at the pace of the system (Leeb et al., 2004a; Leeb et al., 2005). Using the same HMD-based VR setup, Leeb also showed that healthy subjects were able to successfully move down a virtual street via imagined "foot" movement (Leeb et al., 2004b). Later, Leeb and colleagues examined the differences between different types of VR feedback for control of an SMR BCI. Using three healthy volunteers, Leeb et al. compared SMR performance using standard bar feedback with a desktop monitor, virtual world feedback with an HMD and virtual world feedback using a CAVE. The authors found that both, users' BCI performance and preference were highest in CAVE based VR, lowest in desktop VR, and in between with HMD based VR (Leeb et al., 2006).

Friedman and colleagues investigated perceptual differences between the three VR feedback modalities (desktop, HMD and CAVE) for SMR BCI in experiments also reported in Leeb and colleagues (2004, 2004a and 2006). Friedman and others found that when using VR over desktop-based feedback, subjects' BCI performance improved, and their sense of presence and body representation were increased (Friedman et al., 2007). The three subjects in this study reported more natural interactions with the BCI when using VR than with desktop-based feedback. Additionally, these subjects also reported increased motivation when VR was used for feedback, which is of particular importance since motivation has been shown to influence BCI performance (Kleih et al., 2011; Baykara et al., 2015). Similar to the previous studies performed by Leeb and colleagues, Friedman and colleagues found that CAVE-based VR led to greater BCI performance as well as a higher sense of presence when compared to the HMD-based VR. This may be attributed to the reported irritancy in HMD-based VR as well as the narrower field-of-view.

In 2007, Leeb and colleagues further advanced VR-based BCI for navigation by implementing a self-paced SMR BCI with VR feedback where subjects were free to navigate a virtual environment at their own pace. Using ten healthy participants, Leeb et al. showed that self-paced SMR control could be achieved using a 3D wall VR system (Leeb et al., 2007a), and later, with five healthy participants, they showed that a similar level of control could be achieved using a CAVE VR (Leeb et al., 2007b). In the same year, Leeb and colleagues demonstrated self-paced SMR control in a case-study using a tetraplegic volunteer who was able to control a wheelchair in a virtual environment (Leeb et al., 2007c; see also Figure 1, Panel (B)).

In 2008, Scherer et al. and Zhao et al. independently showed successful control of a highly complex self-paced SMR BCI-based navigation in a virtual environment using desktop-VR (Scherer et al., 2008, Zhao et al., 2008). Using different signal processing approaches, both groups demonstrated 4-class SMR control that supported a non-control state, turning left, turning right and moving forward.

Prior to this point, the majority of self-paced SMR-based BCIs typically required extensive training for both the user and the machine (i.e., training of the user to modulate their SMR and training of the machine to recognize that modulation). In 2008, Lotte and colleagues developed a desktop-VR game for an SMR-based BCI that required zero calibration from the computer and showed that without any training, half of the 21 subjects were able to control the BCI with real foot movements and a quarter were able to control it using imagined foot movements (Lotte et al., 2008).

Despite the advances in SMR BCI approaches, a major challenge that still exists today is that SMR-based BCIs do not work well for all users. In 2009, Ron-Angevin and colleagues aimed to address this problem with a systematic comparison between feedback modalities for SMR BCIs (Ron-Angevin et al., 2009a). The study consisted of two groups of 8 healthy participants who trained to use an SMR-based BCI using either a 2D bar on a computer screen or an HMD-VR for feedback. Over multiple sessions, Ron-Angevin et al. showed classification error rates could be significantly reduced indicating that interfaces based on VR can improve BCI control specifically for untrained subjects. Later that year, another approach to improve BCI usability by the same group utilized a low-bandwidth user interface for virtual navigation using a 3D wall VR. Their approach, which mapped an SMR control signal from only two mental states (imagined right hand movement and rest) onto four navigation commands (forward, back, left and right), showed that 6 out of the 7 subjects who participated in the exploration of a virtual environment could improve their performance after each experimental run (Ron-Angevin et al., 2009b). Velasco-Alvarez and colleagues, in 2010, further demonstrated the efficacy of this approach using a 3D wall based VR environment for wheelchair control in 3 healthy participants (Velasco-Alvarez et al., 2010).

Most of the SMR BCI based VR interactions described so far have used low-level commands for virtual navigation, where SMR control signals are translated into incremental movement commands such as "rotate left" or "take one step forward". Each decoded command can take on the order of a few seconds and trajectories must be accumulated through successive low-level commands. Furthermore, the user might be required to correct occasional misclassifications by sending further BCI commands. All this leads to rather slow navigation speeds. To address this issue, Lotte et al. (2010) showed that an alternative interaction modality based on high-level commands, such as moving to a waypoint, allowed participants to increase their speed and significantly reduce the time required to navigate through a virtual environment from first-person perspective.

Expanding upon the idea of using more intelligent control strategies for SMR BCI based navigation, Royer et al. (2010) demonstrated that four healthy subjects were able to fly a virtual helicopter through rings in a desktop-based VR system by thoughtfully mapping BCI output signals to flight control inputs (Royer et al., 2010). In this case, the helicopter moved forward at a constant velocity while the subjects controlled the altitude (up/down translation) and yaw (left/right rotation). In a more complex version of this setup, Doud and colleagues (2010) proved that simultaneous control of forward/backward movement, altitude and yaw were possible using an SMR BCI with a desktop VR (Doud et al., 2010). Furthermore, in 2013, LaFleur and colleagues from the same group demonstrated SMR BCI-based control of a real-world drone through rings suspended from the ceiling of a gymnasium. These studies illustrate how VR can be used as a test-bed for novel applications in a safe and controlled environment before they are tested in reality (LaFleur et al., 2013).

A novel aspect of the opportunities that are afforded with BCI-based VR interaction is highlighted independently by Hazrati et al. (2013) and Scherer et al. (2012). They each demonstrated that SMR based BCIs can be used to interact with massively multiplayer online (MMO) gaming platforms such as Second Life^{TM} and World of Warcraft ^{TM} (Hazrati et al., 2013; Scherer et al., 2012). This work illustrates possible applications of SMR-based BCIs as entertainment for healthy users as well as the possibility of increasing social inclusion for individuals with severe functional disability, as was the aim in related projects (Faller et al., 2013).

Similar to the work in incorporating VR into active BCIs, Reactive BCIs, which rely on brain signals elicited from exogenous stimuli, have also been used heavily with VR technology. Unlike active BCIs, which do not require any external stimuli, reactive BCIs have a unique constraint in that the external stimuli must be incorporated into the VR system. The two most widely studied reactive BCIs are the P300 and steady-state visual evoked potential (SSVEP)-based BCIs, both of which have used VR for stimulus generation as well as for BCI feedback. In pioneering work, Bayliss et al. showed in 1999 and 2000 that P300-based responses can be elicited in a visual oddball task mediated via traffic lights in a natural HMD-based VR driving task (Bayliss & Ballard 1998, 2000). Additionally, Bayliss et al, showed offline that these HMD elicited P300 responses can be accurately detected and classified. In 2003, the same group developed a more elaborate P300 BCI-based VR to interact with a virtual apartment via either HMD or a desktop monitor. Unlike the results shown by Leeb et al. with SMR BCIs, Bayliss et al. found no differences in performance between using the HMD or desktop monitor for P300-based BCI, suggesting that the increased level of presence provided by the VR has less of an effect for P300-based BCIs (Bayliss 2003; Bayliss et al., 2004). Building on this as well as work from Piccione and colleagues in 2008, Donnerer and Steed (2010) studied the effect of different stimulation modalities for the P300 BCI using a

CAVE VR system. In a study involving seven healthy individuals, the authors found that P300 stimuli that were either embedded as objects in the virtual scene or were overlaid on top of the virtual scene had no significant difference in selection accuracy, illustrating the flexibility with which P300 stimuli can be utilized in virtual and possibly real-world environments (Donnerer & Steed 2010).

In a recent study from 2015 involving fifteen healthy users and one locked-in user, Käthner and colleagues used an HMD VR to explore different stimulation techniques for a P300 BCI. They displayed a standard speller matrix instead of a virtual environment in the HMD (Käthner et al., 2015). In one condition, the entire 5x5 matrix of letters was visible and users visually attended to the target letter to spell. In the second condition, the same 5x5 matrix was zoomed in such that only a single letter could be viewed in the HMD at a time depending on the user's head orientation. The authors found no significant difference in P300 detection performance between the two conditions.

Most BCI-VR research for direct control has focused on spatial navigation and exploration applications where an avatar moves through a virtual environment. In 2009, Edlinger et al. developed a BCI-VR task in which the user controls a virtual 'smart home' using a desktop-based P300 BCI setup (Edlinger et al., 2009). In a small study of three healthy users, the authors achieved accurate control of various aspects of the virtual home, such as turning on/off lights and appliances.

As explained earlier, SSVEP-based BCIs, use stimuli that flash at distinct frequencies for tagging different classes or actions. Like the P300-based BCI, SSVEP-based BCIs have also been used in VR where flashing stimuli must be incorporated in the virtual environment in some fashion. In 2005, Lalor and colleagues were the first to overlay SSVEP stimuli onto a desktop based VR environment and demonstrate successful SSVEP BCI control for six healthy individuals. The participants’ task was to focus attention on one of two SSVEP stimuli (representing “move left” or “move right”) in a synchronized BCI setup with the goal of balancing a 3D avatar on a tightrope (Lalor et al., 2005). In a more complex setup using a desktop-based VR, Faller and colleagues (2010) demonstrated that seven healthy individuals were able to control an avatar’s movement with a self-paced SSVEP BCI in multiple conditions from just controlling the avatar's arms to guiding the avatar through a slalom and a virtual apartment (Faller et al., 2010). The authors subsequently extended their earlier work showing three healthy volunteers were able to guide an avatar through an HMD-based VR slalom task by using a self-paced SSVEP BCI system that relied on stimuli in the VR environment (Faller et al., 2010b, 2010c, 2017).

Similar to the P300 work presented earlier, research on optimal methods for integrating flashing stimuli within a VR system has also been explored using SSVEP. One attempt by Legény et al. in 2011 experimented with using naturally integrated stimuli as a way to improve SSVEP stimulus presentation within VR (Legény et al., 2010). In their study, they used the flickering of butterfly wings moving in a virtual environment as the basis for SSVEP-BCI interaction for virtual navigation and compared it to a standard 2D overlay of stimuli and found that even though the subjects felt a greater sense of presence when using natural stimuli, the overall SSVEP performance was lower compared to standard stimuli. This is in contrast to the findings with P300 of Donnerer and Steed in 2010, suggesting that the SSVEP responses are potentially more vulnerable to visual discrepancies potentially caused by a VR system. Despite the degradation in performance, this study demonstrates that SSVEP stimuli can be integrated in an ecological way to create a more natural interaction. Other attempts to improve the integration of flashing stimuli within VR, such as the work done by Waytowich and Krusienski, spatially decouple targets from flashing stimuli in a desktop-based VR, illustrating that it is possible to obtain BCI control without the need to directly fixate on rapidly flashing visual stimuli, which can reduce visual fatigue and allow users to better attend to the task on hand (Waytowich et al., 2015a; Waytowich et al., 2015b).

As mentioned above, Hybrid BCIs combine BCI with other BCI or non-BCI interaction modalities to achieve a higher fidelity of interaction or control (Pfurtscheller et al., 2010). In one of the earliest attempts of using VR and BCI from 1997, Nelson et al. conducted a study using 12 subjects and demonstrated successful control of a virtual airplane displayed within a VR dome using a mix of EEG and EMG signals (Nelson et al., 1997). In another hybrid BCI approach that used both EEG and motor movement, Leeb and colleagues showed that half of fourteen healthy subjects were able to simultaneously use joystick input and an SMR-based BCI to control a virtual penguin in CAVE-based VR (Leeb et al., 2013).

Using a hybrid BCI comprised solely of EEG based signals, Su and colleagues (2011) demonstrated the effectiveness of a sequential hybrid BCI that leverages both SMR and P300 signals to both navigate through a desktop-based VR apartment and interact with devices within the virtual environment (Su et al., 2011).

Unlike the well-researched classes of BCI VR above, there has been relatively little research using passive BCIs with VR. To date, the majority of work has used desktop-based VR in video game applications. Two notable examples use a passive BCI to gather implicit information from the user to change the state of a video game. Mühl and colleagues developed a game called "Bacteria Hunt" in which the level of alpha power of the player affected the controllability of the player's avatar (Mühl et al., 2010). Similarly, in "Alpha WoW", based on the popular MMO World of Warcraft, Bos and colleagues passively monitored the EEG of the player to transform the player's avatar into an animal based on alpha activity (Bos et al., 2010). Additional work using passive BCIs with VR games have explored changing the state of the game environment (Girouard et al., 2013) as well as monitoring content that has been perceived by the player (Zander et al., 2009).

Some more recent approaches have moved beyond direct control and instead used BCI enabled VR to improve human-machine interaction. For example Faller and colleagues (2016) showed that neurologically healthy participants were able to improve their performance in an HMD-mediated VR flight task relative to control conditions when they performed audio-mediated BCI-based down-regulation of their arousal while flying. Additional details of this study and the BCI VR setup and configuration are presented below in Section 9.6.2.

9.3.2 Therapeutic intervention

In recent years, researchers have begun exploring BCI as a rehabilitation tool to treat stroke and traumatic brain injury. It is thought that BCI can help in rehabilitation because it increases immersion and motivation relative to other classic rehabilitation methods like imagined movements. Furthermore, the combination of VR and BCI allows subjects to actually observe their imagined movements, creating “motor resonance”, which may increase plasticity (Van Dokkum et al., 2015).

Holper, in 2010, laid the groundwork for building an fNIRS (functional near infrared spectroscopy)-based BCI for neurorehabilitation. fNIRS is a brain imaging modality that monitors the blood oxygenation near the surface of the brain, reflecting activity in those regions. Holper et al. used a (desktop-based) VR avatar and had subjects perform four grasping-related tasks: 1) observe it, 2) imagine performing the action, 3) both observe and imagine the action simultaneously, and 4) imitate the action. With this experimental setup, the authors demonstrated that activations in the primary and secondary motor areas occur during both overt motor execution as well as observation or imagery of the same motor action, thus illustrating the potential for fNIRS based BCI for neurorehabilitation.

Rehabilitation after damage to motor regions of the brain generally involves exercises previously mediated by the damaged brain tissue. This recruits healthy regions of secondary motor areas to take over the function of the damaged regions. In severe cases, though, a patient may not be able to perform these exercises at all (Holper et al., 2016). In 2013, i Badia et al. developed a BCI system whereby a patient paralyzed in an upper limb can play a game in which a virtual avatar intercepts spheres with its arms. The patient controls the arms with imagined movements and sees those movements carried out on the screen in a first-person perspective. This recruits the mirror neurons and activates the motor system more extensively than if the task was performed without a BCI. The experiment was carried out in nine healthy subjects as a proof of concept. Subjects achieved a successful functional performance rate of 85 %. In a separate experiment in the same study, i Badia found that by having subjects simultaneously mimic the actions of an onscreen avatar and imagine the movement (i.e. motor activity and motor imagery), they were able to recruit more task-related networks than by doing either activity alone.

In 2015, Pichiorri et al. performed a randomized clinical trial, testing the functional benefits of stroke rehabilitation with a BCI. They divided twenty-eight hospitalized, sub-acute stroke patients into a BCI group and a control motor imagery group. For the BCI group, patients were seated at a table where their hands were covered in a white sheet. A BCI was set up so that when they imagined movement of their affected hand, a hand projected onto the sheet would perform the imagined movement. The motor imagery group underwent a comparable therapy routine except they were instructed to imagine the movements without any BCI feedback. After a month of therapy, the BCI group performed better on the Fugl-Meyer Assessment (an assessment of motor function, balance, sensation, and joint function), Medical Research Council scale for muscle strength, and National Institute of Health Stroke Scale. They also found that the BCI group had a significantly more robust desynchronization in the alpha and beta bands of the centroparietal regions of the ipsilesional hemisphere. The authors attribute the difference to the visual feedback given to the BCI group, allowing patients to continuously improve in their task performance.

In the past few years, researchers have carried out proof of concept experiments that incorporate BCI and VR into more sophisticated rehabilitation regimens. In 2016, Luu and colleagues showed that BCI can provide an alternative to rehabilitative exoskeletons in the field of gait rehabilitation. They created a VR avatar whose gait was controlled by a BCI and showed that subjects could control the gait even under perturbations. In another study in 2015, Brauchle and colleagues sought to enhance exoskeleton-based therapy. They were concerned that exoskeletons provide too much support during exercise. To address this issue, the authors developed a BCI-exoskeleton system that only provided support when the subject was both making an effort to move and his brain was responsive to peripheral input. The BCI was simultaneously used to generate visual feedback via an avatar (desktop VR). Finally, in 2016, Grimm and colleagues built a proof of concept rehabilitation system that combined neurofeedback, neuromuscular electric stimulation (to restore muscle strength), and an exoskeleton (to improve range of motion and intensity of training). In his system, the joint angles of the exoskeleton were used to generate a 3D avatar that was displayed to the subject (desktop-based VR). They found that by combining these three methods of therapy, they were able to augment upper limb function and brain activity during rehabilitation.

In more basic research, Perez-Marcos and colleagues (2009) showed that healthy subjects were able to feel “ownership” of a virtual hand if it responded to motor imagery, which as they argue might aid in rehabilitation applications.

9.4 Augmented reality and brain-computer interfaces

Augmented Reality (AR), where sensory input is only partially replaced or augmented, has recently been applied to brain-computer interfaces to develop novel feedback interfaces that uniquely blend the user's reality with virtual reality. In 2010, Faller and colleagues showed that three healthy subjects were able to guide an avatar along a course in HMD-mediated AR using an SSVEP control signal. The avatar appeared in the AR surrounded by three flickering SSVEP icons. Using this setup, the subjects were able to successfully guide the avatar through a course of obstacles constructed in the AR (Faller et al., 2010b, 2010c, 2017).

Also in 2010, Kansaku and colleagues were concerned that successful BCI paradigms may not translate to VR and AR settings. Neuroscientists found that when humans look through new visual perspectives (i.e. through a monitor), their body scheme changes. The usual experience of being located inside one's own body is disturbed, and there is an illusion of swapping bodies with another (Botvinick and Cohen, 1998; Petkova and Ehrsson, 2008). Kansaku and colleagues studied whether this would affect the P300 signal by having ten subjects control a robot in a separate environment. A video feed from the perspective of a camera mounted on the robot was displayed to subjects on a monitor, and a modified P300 speller was overlaid. They found that the subjects were able to control the robot despite the changed perspective (Kansaku et al., 2010).

In 2015, Petit and colleagues built a BCI-based robotic control system that compensates for the low frequency and accuracy of BCI signals. They took the video feed from cameras mounted on a robot and overlaid flickering icons to be recognized in the SSVEP signal. They used object recognition, mapping techniques, and shared control to augment the BCI control signal (Petit et al., 2015).

Finally, Kim and colleagues (2016), used BCI and AR to explore human-animal interaction, creating a BCI controlled "cyborg-turtle". They mounted an apparatus onto four turtles that included a camera as well as a rotating cylinder that could obstruct the turtles view and thereby guide it in the opposite direction. Five users wore HMDs in which they could see the video stream from the turtle and juxtaposed flickering SSVEP stimuli. Subjects successfully guided the turtle using the SSVEP-based control signal.

9.5 Example architecture for BCI/VR setup

Apart from custom software, there are several openly available platforms that can be used to implement BCI VR/AR experiments. For example, OpenVibe (Renard et al., 2010), an integrated environment that features visual programming or BCI2000 (Schalk et al., 2004), a particularly thoroughly tested BCI platform. We review a setup that allows researchers to flexibly interconnect functionality from different software packages and toolboxes, allowing for a highly customizable, extensible, cross-platform setup that is particularly well suited for rapid prototyping of VR/AR experiments. At the core of this approach lies a software package called Labstreaming Layer (LSL; Kothe 2013), that relies on software-based, distributed signal acquisition and synchronization at sub-millisecond precision. It consists of a cross-platform library, that can be used by any application written in C, C++, Python, Java, C# and Matlab. LSL facilitates the streaming of data to and from any application or device on a network. With LSL, applications can easily record, store, process or visualize any number of bio-signals from one or more subjects with accurate time-stamping and synchronization including experimental events. LSL comes pre-loaded with dozens of applications and new applications can be easily created as communicating data via the LSL library is a matter of only few lines of code in any of the supported languages. In this BCI/VR approach, LSL is used to network together the various experimental modules and components as shown in Figure 2.

Using LSL, signals from different sources (i.e. EEG, eye-tracker, mouse, keyboard, joystick, video, etc.) can have completely different meta-information and sampling rates (including an option for non-equidistant sampling). The LSL application LabRecoder can save any set of such streams into files of the recently introduced extensible file format (XDF, Kothe & Brunner 2015). Such multi-rate signals in XDF, can then be seamlessly displayed in the cross-platform visualization application SigViewer (Schlögl & Brunner 2008).

For VR visualization, this experimental setup relies on the openly available software framework NEDE (Jangraw et al., 2014), which runs in Unity 3D, a cross-platform 3D environment (Unity Technologies, San Francisco, CA, USA).

As for processing of the signals, the present setup uses BCILAB, a thoroughly documented Matlab toolbox, that supports relevant procedures for all major steps in BCI processing, from pre-processing, over feature extraction to classification for all major BCI approaches (Kothe & Makeig 2013). Figure 2, shows a general system architecture overview diagram for the presented setup.

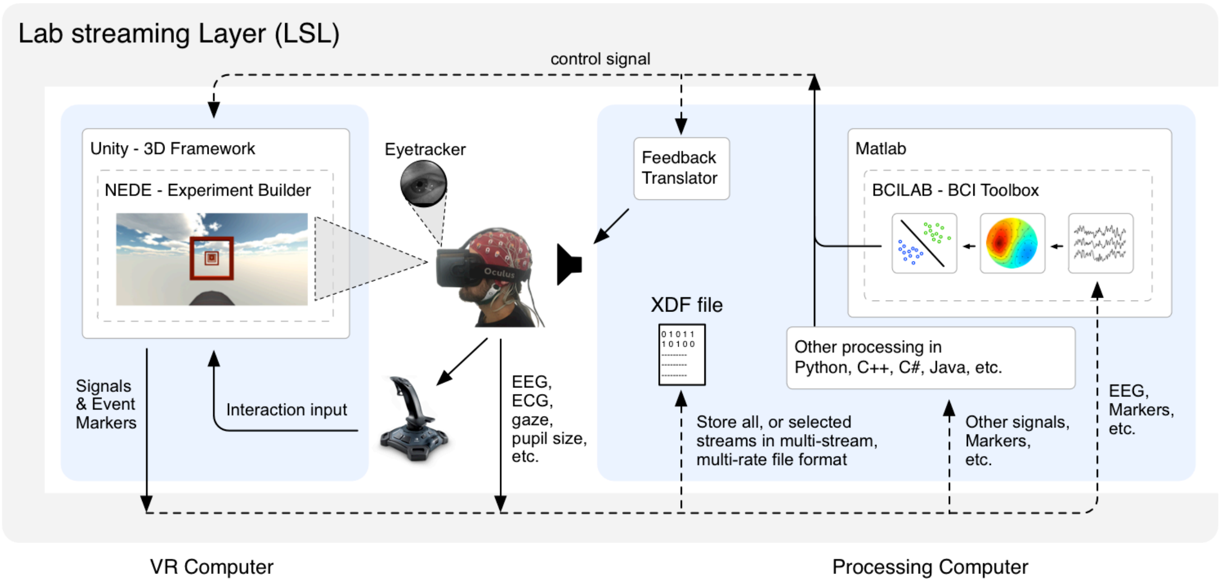

Figure 2: Architecture overview diagram for the presented exemplary BCI VR/AR framework. The VR experiment (NEDE/Unity-3D) is displayed via HMD (Oculus) while signals are simultaneously recorded and processed via BCILAB for real-time feedback. The oculus rift head-mounted device in this setup is retrofitted with an eye-tracker by SMI (SensoMotoric Instruments GmbH, Teltow, Germany). This setup allows for both open and closed-loop experiments.

9.6 Validation of example architecture

9.6.1 Technical validation – Latency and jitter of processing

Labstreaming Layer was developed and tested at Swartz Center for Computational Neuroscience at University of California San Diego, and, according to the authors, the precision of its timing can be assumed to be at sub-millisecond level in a local network (Kothe 2013). LSL records a timestamp for every acquired sample. This allows one to debug systems and perform post-hoc validation in terms of sampling jitter and delay on recorded data. In Figure 3 we show histograms of sample-frequencies for EEG acquired at 2048 Hz and signals from unity at around 75 Hz. We see that the actual sampling rates are very close to the expected sampling rate for this setup.

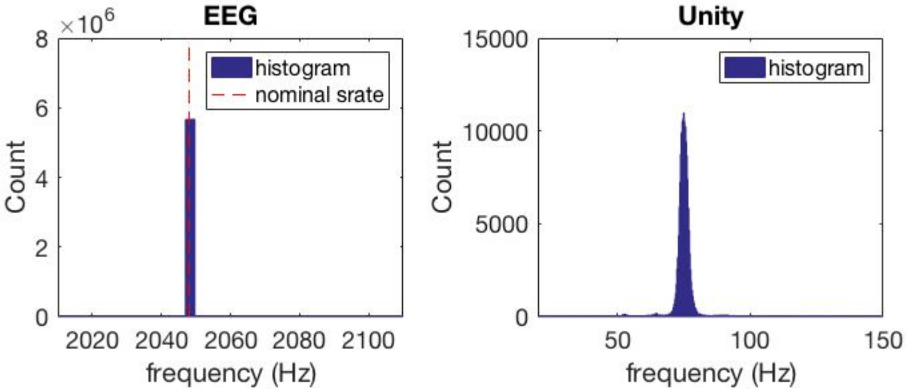

Figure 3: Histograms for sample-times for EEG (peak at 2048 Hz) and for signals from within Unity (peak at 75 Hz). The screen refresh rate in Unity is not fixed, which explains the absence of the vertical line indicating the nominal sampling rate.

9.6.2 Experimental validation

Faller and colleagues (2016) used the BCI VR framework described in Section 9.5 for a preliminary study into the hypothesis that BCI based down-regulation of arousal in a closed-loop setup could increase decision flexibility to a degree where human performance could be improved in a flight task with increasing difficulty. In the VR paradigm, healthy participants had to fly a plane through a corridor of red frames. The vertical arrangement of these frames was according to a sum of sines, and the size of the frames decreased every 30 seconds, thus increasing task difficulty. Failing to fly through only one of the frames ended a run. The authors recorded EEG, electrocardiogram (ECG), gaze, pupil diameter, electrodermal activity (EDA), electromyogram (EMG), respiration, joystick input, plane movement, head orientation and paradigm specific markers.

The nature of the flight task requires that there exist physical or performance boundaries that are task-critical, simulating what is referred to as a boundary avoidance task (BAT) (Saproo et al, 2016). The BAT is often used as a surrogate task to investigate human-machine interaction that is the basis for pilot induced oscillations (PIOs). The more realistic the BAT task, the greater the likelihood of generating a neurophysiological state that captures the real-world scenario, namely a pilot losing control of their aircraft via destructive man-machine coupling.

This study found that the BAT employed in this VR environment strongly elicited PIO like behavior and that a closed-loop BCI that tracked neurophysiological signatures of arousal and cognitive flexibility could be used to develop an intervention that improved flight performance relative to control and sham conditions.

9.7 Limitations of VR and AR in the context of BCI

Creating VR or AR scenarios typically requires 3D modeling and/or programming skills, as well as unique knowledge and understanding of the environment to be simulated. This problem is mitigated, when using specialized frameworks like NEDE, where tools and existing code already handle most routine tasks. This allows the scientist to focus on experimental design. A remaining problem is that some VR/AR users experience nausea in VR, which is believed to be related to a sensitivity of these users to incongruencies between the inputs to visual and vestibular system. Thus some populations may not be a good match for VR/AR experiments.

9.8 Future developments

9.8.1 Novel interfaces between user and VR/AR

Future technological improvements to VR and AR could involve virtual retinal displays (VRD) that project images directly onto the retina, thus producing a sharp, high-contrast picture (Pryor et al., 1998). Another approach, which is currently under development, is bionic contact lenses that receive both power and information wirelessly to display images to the user via a contact lens (Parviz 2009). Other potential approaches aim to completely bypass the input sensory pathways of the peripheral nervous system, those normally responsible for example for feeling the texture of objects, by stimulating the brain directly (O'Doherty et al., 2011).

9.8.2 Novel paradigms – opportunistic sensing

As we have said, integration of BCI with VR offers a convenient and promising platform to investigate basic questions in cognitive neuroscience using more naturalistic and complex, yet controlled environments. For example, future paradigms, some of which would employ closed-loop neurofeedback, could investigate cognitive phenomena ranging from emotional regulation to dynamic decision-making. The collection of neurophysiological data across multiple subjects interacting with each other in virtual worlds may provide new insight into social cognition. In fact, opportunistic sensing of cognitive state using BCI platforms within complex virtual environments is one avenue for potentially integrating non-invasive human neuroscience with big data analytics. The level of immersion and entertainment value of VR potentially enables collection of massive EEG and physiological data both longitudinally as well as across large and diverse subject populations. New neural correlates may be revealed by using machine learning and big data tools to discover relationships between the neurophysiological data and the complex events and interactions in these environments.

Integrated BCI and AR systems hold promise for new ways we will interact with the real world. Instead of recommender systems and user models being developed by monitoring what we click on when using our computer or smart phone, opportunistic sensing of cognitive data, via BCI enabled AR, could be used to label elements in the world that we find interesting. By combining opportunistically-sensed signals with metadata in the environment, one can provide immediate information to the individual, including a model that provides insightful recommendations (Did you just see someone walking down the street that caught your attention?). By opportunistically sensing the orienting response and snapping a photo with your built-in AR camera, that image can be sent to the cloud, compared against a database, and up pops her name on your AR display. It jogs your memory and you remember you went to school with her! This type of "just in time" metadata derived from linking opportunistic sensing and cloud-based analytics has applications that are not just a social network novelty but could enable new classes of cognitive orthotics. As the population ages, new type of platforms will be needed to help us maintain our cognitive capabilities, for example, "putting a name to a face". Opportunistically sensing neurophysiological correlates of orienting and familiarity, and using these to inform computer vision and machine learning analytics so that they can provide individuals with metadata and context, is just one such way that BCI AR systems will change how we interact with our world.

9.9 Conclusion

The current state of research indicates that BCIs can facilitate natural, seamless and intuitive interaction with VR and AR, and preliminary attempts to use VR and AR for clinical purposes like stroke rehabilitation also appear promising. Future technological improvements like bionic lenses and concepts like opportunistic sensing will likely make BCI VR/AR systems even more immersive and pervasive.

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