Acceleration of Therapeutic Use of Brain Computer Interfaces by Development for Gaming

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Abstract. Brain computer interfaces (BCI) are the foundation of numerous therapeutic applications that use brain signals to control programs or to translate into feedback. While the technical creation of these systems may be done in the lab with limited design expertise, the translation into a therapeutic calls for the engagement of game designers. This is evermore true for BCI in virtual reality (VR). VR has the potential to elevate BCI in embodiment and immersiveness. These traits are key for neurofeedback therapies for neurobehavioral conditions like anxiety. The cooperation between game designers and scientists overcomes the hurdle in transforming an experiment into a tool. More often than not, BCI on the road to therapeutics or other practical applications are launched in original or adapted games to demonstrate the usability of the platform. In the absence of partnerships like this, slow or stalled progress ensues on the scientific translation. We demonstrate this principle in a range of examples and in-depth with *Mandala Flow State*—a VR neurofeedback system that first served as an interactive installation in an art museum.

Keywords: Virtual reality · Neurofeedback · Brain computer interface

1 Introduction

Brain computer interfaces (BCI) are the modern-day science fact of how our thoughts and intentions are used to control electronic devices. In short, brain signals read in by sensors are processed to distill a discrete and discernable signal that is mapped to control parameters in the computer program [1]. While the primary uses of this technology are for medical purposes, such as control of robotic arms or assistive devices [2], one arm of acceleration for the science has been gaming [3, 4]. In the spirit of keeping with the first video game, the earliest demonstration of BCI was done with a game of pong. It has followed as the proof-of-concept game for emerging BCI technologies, as highlighted in Pong. Mythos exhibition (Germany, 2006–2007). In a few training sessions, a user can implicitly learn to move the paddle right or left with a single electroencephalogram (EEG) channel from the frontal lobe. This beginning then led to BCI for more complex

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games, such as World of Warcraft [5]. The sense of embodiment is promoted when the device controller is removed from the picture.

In furthering the immersive embodiment of the gaming environment, virtual reality (VR) gaming creates a heightened and broadened sensory experience. Imagine the additive perception of engagement if brain signals are used as the controller in a VR first-person game. For example, take the popular Half-life:Alyx and replace the hand controller with built-in EEG sensors such that your intent is translated to digital action. Valve corporation has made the bold statement at GDC 2019 that they are investing in research to integrate EEG into gameplay for a variety of features, not simply substituting the controller. While this makes for a fun experience, the societal benefit is agnostic. However, the same properties of engagement and embodiment can be carried over for therapeutic uses of VR.

VR is one platform for digital therapeutics. Digital therapeutics use monitoring programs and devices to provide user feedback in the management of a medical condition. A longstanding therapeutic is neurofeedback. Neurofeedback therapy gamifies modulation of patterns of brain activity in order to up or down regulate neural pathways that are linked to behaviors [6]. For example, strengthening alpha frequency waves in the frontal lobe is associated with reduction of anxiety [7]. Alpha frequency is visualized in the interface and with practice, the user should be able to change that visualization in the targeted manner. Presently, many research groups, including ours, and some companies are adapting neurofeedback into VR games, though none are to market as of yet. The goal is to improve the potency of neurofeedback with greater engagement in VR.

In this paper, we will explore the role of BCI in recreational gaming, followed by the transformation into gaming for virtual reality applications. Lastly, we will demonstrate how the principles of BCI gaming may be adapted to therapeutic neurobehavioral applications.

2 BCI Gaming

BCI in gaming takes two roads (Fig. 1). One is the identification of mental states by EEG in order to modify the gaming experience in response to these fluctuations in activity. This can be achieved with a few dry electrodes over various locations of the head. A mental state is typically detected by an average signal over seconds of time, typically calculated by a power analysis of frequency bands [8]. This is fairly straight forward in terms of hardware, signal processing and analysis. The second are discrete stimulus-driven responses that are used for specific actions in the games [9]. This depends on more sensitive, numerous and fine-tuned EEG sensors whose signals are converted to event-related potentials (ERP) on the tens of millisecond scale. The key component is isolating reliable signals associated with the intent of the user, in this way substituting for the translation of action through a manual controller. Intent and mental state are two types of distinct signals with categorically different analytical methods. Consequently, they need to be considered separately.

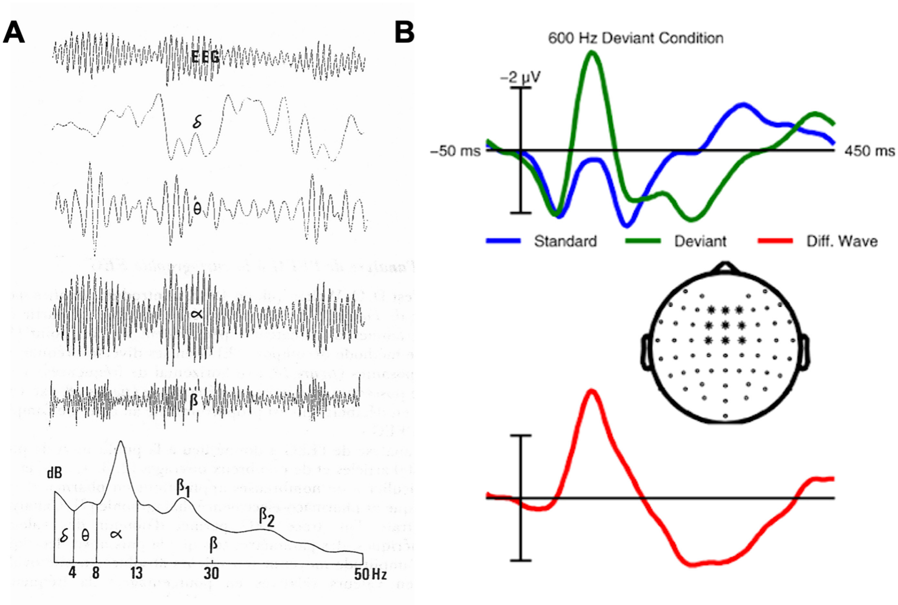

Fig. 1. Examples of EEG analyses used in BCI applications. (A) From raw EEG, frequency bands are separated between 1 and 50 Hz. Then a power analysis is applied to the frequency range. The average over a band is used as the feature for smooth BCI controls. (B) Event-related potentials (ERP) are extracted from raw EEG by time-locking to a stimulus provoked response over a set of channels. In this example, mismatch negativity ERP is shown over a 450ms window. ERPs can be used as precise control signals in BCI applications. (a) CC by Albin Michel, Collection "Sciences d'aujourd'hui", Figure 18, page 142, 1987. ISBN: 2226028716. (b) CC by Front. Neurosci., 30 December 2013, Figure 1. https://doi.org/10.3389/fnins.2013.00265.

2.1 Traditional Gaming

A proof-of-concept demonstration of BCI has been well documented by University of Twente [10] and Graz University of Technology researchers [11] in the adaptation of World of Warcraft play with EEG mental imagery or slow wave oscillations. Using EEG channels positioned over sensorimotor cortices, the system learns to recognize directional movements. With practice, users are able to reliably produce these signals as intuitive control of the game play. These groups even incorporated neurofeedback in the form of shapeshifting characters. When indicators of stress were detected, the player changed to a monster-like character. The player would need to relax to return to their default state [11]. This work is nearly a decade old and has not come to market.

The lack of progress is in part due to the limitations in wearable and consumer accessible EEG devices of the time. Significant progress has been made in hardware for consumer EEG headsets and in the algorithm development for signal analysis (Fig. 2). Wireless Bluetooth technology and dry electrode sensors are the two advances that enabled the hardware change from the high-density gel electrode caps wired to preamplifiers then processed through PCs. For software, application of real time signal processing and rapid and adaptable machine learning algorithms have transformed what used to take 30 min in the lab down to 1–3 min. These range from single-channel electrodes (NeuroSky) to 14-channel headsets (Emotiv EPOC X). Both Neurosky and Emotiv have also shown the community that their devices can be used in simple BCI games. The Muse, another dry electrode device, has successfully been adapted into the game *MindBall Play*, in which marbles are raced through complex winding paths [12]. While the demos and even marketable products are completed, iterative adaptation for more games and broad user adoption remains elusive, likely due to the lack of penetrance of the market for consumer EEG.

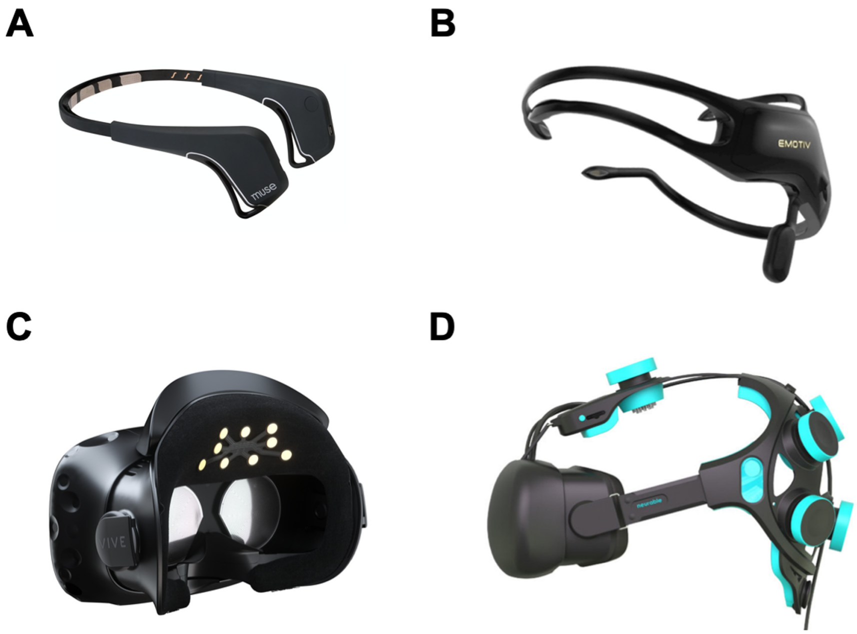

Fig. 2. Consumer devices for EEG and integrated EEG and VR. (A) 5-channel Muse 2, (B) 5-channel Emotiv Insight, (C) Looxid Link affixed to HTC Vive, (D) Neurables HTC Vive with Wearable Sensing electrodes. Each device has different electrode sensor design and distribution over the head. The fit of each is also distinct. For these reasons, the usage in BCI applications are not interchangeable and each have uniquely suited contexts.

Sometimes video games are used to demonstrate a therapeutic proof-of-concept. For example, a functional electrical stimulation (FES) BCI to play Guitar Hero [13]. In this system, electrical signals directly measured from the primary motor cortex are read in and trained to detected combinations of motor messages through mental imagery. This is then mapped to an output of stimulation electrodes to the forearm that activate the combination of muscles associated with the intended movement. The beauty of this demonstration is in the control of each finger in real-time. Now for the paralyzed individual, the function he was most hoping to regain was certainly not Guitar Hero. However, by using the game to train the algorithms for individual finger modulation, further functional movements, like a grasp, can be effectively learned and programmed. Without question, spending hours playing Guitar Hero was more engaging for the patient than repetitively tapping each finger until pattern detection was reached, which is traditional manner to train a BCI controller.

2.2 VR Gaming

The first true BCI VR game, *Awakening*, was developed with Neurable's technology in 2017. Neurable adapted the HTC Vive headset and Wearable Sensing dry electrode EEG to a single piece of hardware. The software analyzes the signals from the parietal and occipital lobes to extract P300 ERPs. The P300 is an indicator of visual attention. Neurable has adapted this signal into a selection tool in the game. So rather than point to or scroll to what you want on the screen, you look at it. For Neurable, gaming is not the primary goal. Their long-term applications are for integration of BCI into simulation training and testing as well as novel devices for more consumer applications. Despite these being their stated goals, investment for this young company first came in the form of VR game development.

Valve Corporation is actively researching how BCI may be used in gaming as revealed at the 2019 Game Development Conference. While the company did present the progressive work of more intuitive control of games through EEG signals paired with eye tracking and gestural control, the focus was on evaluation of mental states during play to adapt the game environment in response to affective dips. For example, a player may become disengaged with the game as noted by decreased attentiveness (lower beta frequency power), which could trigger an exciting turn around the next corner. Difficulty of the game may instead be determined by cognitive load in contrast to a preselected level. In these ways, game play may feel "just right" to the player in this highly personalized and dynamic experience. The adaptive aspect is similar to neurofeedback games, which adjust the difficulty factor based on performance.

The advantages of developing BCI for the context of gaming are that hours of data can be collected from a distributed network of thousands of people. Most research labs do not have the reach or the funds to acquire data at that scale. Individual lab studies typically run for about 15 min and may have a few dozen participants. The great quantity and diversity of data from game play can then drive robust machine learning models for generalization and sensitivity in consumer applications for wellness or market research as cited use cases by Looxid Labs.

Looxid Labs is a relatively young company that is on the forefront of EEG integrated VR. In contrast to Neurable, which positions the electrodes broadly around the scalp, the LooxidLink adheres to the front of the headset with a concentrated set of electrodes over the anterior frontal lobe. This is another example of a gaming introduction to neurofeedback. Their demo games are all driven by classic mental state indices, including the *Mental Playground*. In this game, neon 3D shapes are programmed to rise and fall with fluctuations in concentration. Looxid Labs makes their SDK available for others to develop applications using their hardware and software. For VR BCI that utilizes intrinsic activity, rather than evoked responses, an integrated platform like this may be used for extended training or therapy.

3 Digital Therapeutics

Nearly all current digital therapeutic companies have gamified their therapies. Curiosity, challenge, aesthetics and engagement are critical for a successful implementation of a therapeutic aiming for behavioral change. A handful of companies, highlighted in this section, have shown what can be done with VR to enhance user engagement and efficacy through embodiment, high stimulus environments, reward and challenge. Game designers and software developers are essential players along with the scientists and physicians of therapeutic BCI endeavors, like neurofeedback-integrated VR games. The cooperation between these disciplines are overcoming the hurdles of access to potential benefits of neurofeedback therapy.

3.1 Traditional Neurofeedback

Neurofeedback is a therapeutic adaptation of closed loop BCI. The same components are in place—sensor of brain activity, processer, effector [14]. The user at the center of this loop is learning to control the effector, just like a BCI game or a tool. In stark contrast is the actual goal of the activity. In neurofeedback, the control or modulation of the game is simply an avenue to change the targeted pattern of brain activity. Neurofeedback therapy is agnostic as to what the effector may be, as long as it is effective in engaging the user long enough to make lasting neuroplastic transformations [8]. The reality is that any game or BCI will make changes in the brain as that is what defines learning of all types. Neurofeedback therapy is unique in that its purpose is only relevant as transfer learning. Becoming proficient at the neurofeedback game, must carry over to the behavioral or mood correlate outside of the game. For example, a therapy that targets sustained attention must show that the user then has improved focus at work. Consequently, the bar for performance is greater for the BCI in neurofeedback therapy than in a gaming context.

While specialized neurofeedback programs have been developed for neuropsychiatric clinics like the Drake Institute, these protocols are not accessible to the masses. The personalized therapeutic plan requires high density EEG that is quantitatively mapped [15]. For each patient, the "abnormal" regions are localized and the degree and direction of change is determined. That local signature is then programed as the input to the neurofeedback training game. Over six weeks of daily practice, the brain gradually changes. Assessments are completed to see if the patient has improved upon standardized psychometric scales or may have reduced sensitivity to episodic triggers (as in PTSD). This level of commitment is called for with psychiatric conditions that are debilitating. However, there is an existing need for brain training in subclinical populations and neurobehavioral conditions that interfere with peak performance. This is the concentration of our team's work.

A key democratization of neurofeedback has been the emergence of consumer EEG devices that are sold as part of wellness packages (Fig. 2). The Muse, which is marketed as a meditation aid, is distinctly in the "wellness" market and not for therapeutic use. Emotiv is presented as a tool for a broad set of portable EEG applications, especially research. Emotiv has demonstrated several BCI proof-of-concepts [16]. One of the most outstanding is a demonstration of the Emotiv EPOC used in a serious game for focus training by using the pre-defined mental commands [17]. On average, players showed an 8.25% increase in focus based on EEG measurements compared to keyboard control of the game. As described earlier, Looxid Labs exclusively develops BCI hardware and software for VR with a Unity SDK. The potential for novel and immersive game development is thus open-ended and may be expanded richly by the community at large by partnering with the company. Importantly, each of these companies have devices that run for $300 USD or less, making them an attainable investment.

One example of how a single channel EEG system (MindWave by Neurosky) may be used in treatment of anxiety is shown in the game *Mindlight* [18]. In this game, the frontal alpha and beta frequency ranges are used as different reward parameters in the neurofeedback training to improve self-regulation of anxiety. Targeting 8–16 year-olds with autism spectrum disorders, the game setting is a magical mansion with monsters that are vanquished by the player's light, which is controlled by EEG correlates of focused relaxation. The outcomes of the first trial showed that parents report changes in symptoms, while children do not [19]. While the outcome is not undoubtedly convincing of the effect, the game design in *Mindlight* is on par with simple video games children may otherwise play and were successful in consistent player activity over six weeks, showing strong engagement.

A similar model to what our team is aiming to achieve is practiced by MyndLift [20]. MyndLift uses the Muse EEG device, like we do, and tablet or smart phone delivered neurofeedback system. Any individual may sign up via their website and be paired with a neuro-coach. A subscription fee is collected as an active user. The Muse is a five-channel dry electrode array that is position over anterior frontal and temporal locations. These sites are sufficient to reliably and robustly measure spectral frequencies from 1 to 50 Hz. Standard power analyses are conducted followed by calculation of mental state indices (e.g. "attentiveness"). Either may be used to create a control parameter for the neurofeedback training. The timeline of a therapy is similar, as this is determined by the neurobiology of synaptic remodeling, which takes roughly a month to stabilize. The advantage of the Myndlift system is that it may be practiced at home with easy to use technology. Working under the assumption that a person already has a tablet for general usage, the only specialized hardware needed is the Muse, which is priced lower than a smart phone. Further the monthly subscription fee is a fraction of the cost of an hour with a therapist. This is one path of increasing accessibility to mental health services, which are impacted by limited number of clinicians and cost. While Myndlift is a significant advance in overcoming hurdles of access, the brain training games are graphically simple and gameplay is very one-dimensional, in our opinion. By transforming this model to include a VR option, the user engagement, compliance and efficacy may be improved. We demonstrate a proof-of-concept of this with *Mandala Flow State* as described in Sect. 4.1.

3.2 Enhancement of Digital Therapeutics with VR Features

Gaming in a VR environment enhances the user experience through its immersivity. This is not simply due to the 360-degree views. Rather it is the visual illusion embedded with an array of interactive and sensory dimensions. These affordances are the basis for building a sense of presence and embodiment in the VR environment. The perceptual trickery may be used to more effectively train a BCI for gaming or therapeutic purposes.

The embodiment of the player in a VR space has been adopted into neurorehabilitation interventions [21]. The real time synchronization of an avatar has enabled improved in-home rehabilitation for stroke recovery and pain management. For example, Cognivive recently received FDA clearance for a VR neurorehabilitation system. The stroke recovery training is in the context of a beach resort that includes a social component and puzzle solving in the context of completing physical rehabilitation at home. Likewise, Karuna Labs uses VR therapy for chronic pain management. In this experience, patients are mirroring an avatar to promote virtual embodiment, which lessens the perception of pain during physical therapy. With similar goals, MindMaze is developing a VR headset with integrated EEG for virtual embodiment training for neurorehabiliation [22]. Prior to these VR-based interventions, the options to patients were more limited and difficult to access and painful.

Interactive affordances are a constant innovation in VR gaming. Hand-based gestures to virtually touch something with bare hands or haptic feedback gloves, like those from HaptX, imbue a sense of verisimilitude to the experience. The hand can manipulate and grasp affordances such as switches, dials knob and tools. The tactile simulation may be more convincing in VR rather than screen-based games due to the circumscribed 3D visual field. For interventions targeting conditions with attention challenges or sensory processing, immersivity and presence are critical for efficacy. For instance, by the character of the condition, people with attention deficit disorders are easily distractible by their own thoughts or their environment. Creating a complete audiovisual space with tactile stimulation helps to overcome that distraction by providing sensory input that shields the external world and is more potent than their internal melliu.

These unique affordances of VR may improve the likelihood that users engage with the therapeutic game. Greater engagement does not simply mean spending more time with the game. Engagement can be synonymous with attention. When the goal is to promote self-regulation of attention, the neurofeedback system will train at a faster pace due to this reinforcement. The quicker learning and reward are an encouragement to users, which may motivate users to continue use of the VR game to their therapeutic endpoint of 4–6 weeks.

Gaze direction is readily decoded from a VR headset position or with integrated eye trackers, such as in HP Reverb G2 Omnicept. Gaze is another indicator of directed attention and intent. This may be used in combination with brain signals to reward the learning goals. For example, the gameplay may be a visual search task. When the player fixates on the target and the associated neural correlate increases in conjunction, a pop-up reward may appear (gaining points or prizes). An elegant application of gaze control is demonstrated in *Dreams of Dali* VR experience created for the Dali Museum in St. Petersburg Florida. The visitor simply looks at the glowing orb for three seconds and is then teleported to the next position in an immense world made of his paintings' imagery. This created a seamless teleportation that flies you to your destination. The teleportation illustrates how transitions may feel naturalistic, rather than artificial scene switching. This feature is important for maintaining presence in the virtual environment and concentration on the gameplay.

VR games are rated on immersion and comfort on top of the actual gameplay in contrast to screen-based 2D games. VR games, as a new medium, have links from past titles with modifications for player immersion. The titles can be part of a larger cosmology, such as Star Wars or Harry Potter. The game can also fulfill a filmic narrative within the cosmology allowing the gamer to participate within that world. Star Wars titles done in VR, by the spinoff ILM X Lab, have a character adoption feel that the films could not attain. A narrative is given to promote the player's transformation into the character. For example, the player becomes a fighter pilot for the Rebellion. These games are an expansion in the Universes they create that give a greater sense of belonging. The personalization in the storyline certainly strengthens retention of gameplay, which may be translated into methods for greater engagement in therapeutic VR games. For therapeutics games intended for teens, alternate worlds inspired by popular culture and film may be an effective way for them to connect to the activities and create personalized and elaborate experiences that grow and change over the training period.

For an effective digital therapeutic that is delivered in-home, the importance of user motivation cannot be ignored. Liken this to the info sheet on exercises given to you by your doctor to do at home to reduce back strain. How effective is this intervention? How many people are motivated and organized enough to do boring, repetitive, and sometimes painful and difficult exercises when there is no encouragement or accountability? The same principle applies to any behavioral modification regiment. In-clinic neurofeedback has the advantage of a therapist working with the user in person on a set schedule. Without this structure in place, the factors of the personal motivation and enjoyment weigh heavier. VR capabilities have the potential to make a greater impact on this dimension than other modalities.

4 BCI Neurofeedback in VR

In our opinion, the next milestone in BCI would be to take advantage of the immersive quality of VR to change the way neurobehavioral therapies are conducted. Neurofeedback therapy, as described in previous sections, is a powerful tool when done well—accurately identifying the source signal, adaptive responsiveness of the BCI, and user adherence over six weeks [24, 25]. Unfortunately, the implementation often fails to meet these criteria [8]. The work of our team aims to address some of the weaknesses in the current practices. In particular, user engagement and compliance as well as creation of an environment that promotes the desired effect.

4.1 Mandala Flow State

One of the most reliable EEG signals in the frequency domain is the alpha power over the frontal lobe [23]. This has been used in neurofeedback therapies to improve relaxation, decrease stress and anxiety, and improve focus [23]. Our group has used this signal to drive a VR experience that targets focused relaxation [26] (Fig. 3). The system uses the Muse EEG headset for signal detection and preprocessing. The alpha frequency from the frontal electrodes are extracted and processed into standardized values. The detectable fluctuations in these signals are calibrated with a difficulty factor. The VR application is developed in Unity3D. The processed EEG signal is a control parameter for the game. The VR experience is delivered through an Oculus Rift S headset. This framework opens the door to many variations on a theme of modifying patterns of neural activity and behavior.

In our prototype, we selected a context that would promote a state of focused relaxation via cultural association and sensory experience. The environment created for focused relaxation was thus a mandala, a tried and true meditative visualization aid [27]. The feedback parameter is also an intuitive link to the desired mental state. This version was a procedural mandala that was uniquely generated in each run. The soundscape was an ambient melody layered with 10–12 Hz binaural beats and “Om” chants. The transparency of the mandala and the gain of the chants were parallel feedback channels that changed with alpha power. The first testbed for our prototype was a brief simulation run with pre-recorded EEG. This was run on 38 people over three hours, with a waitlist of 50 people, at the San Francisco Night of Ideas 2019 [28]. The high traffic at our installation showed a significant level of engagement and interest in this platform by the public.

Subsequently, we redesigned the mandala to reflect a more authentic aesthetic and perceptible feedback (Fig. 4). This was achieved with a fog filter over the generative mandala inspired by Tibetan Buddhist mandala architecture. The dynamic aspect of the mandala was how it envelopes the 3D visual space and creates the illusion of traveling movement as the mandala gradually grows from the central point of view. Each instance of the application generates a new design of the mandala from a library of colors and elemental patterns. The soundscape accompanying the visual experience is an original digital composition that follows a template of shifting complexity and dissonance to promote focus and prevent passive viewing. The alpha power from the brain activity was inversely linked to the fog shader in order to figuratively clear the fog from one’s mind. The summative reward is to see the complete mandala clearly before it is swept away like sand. Consideration of both the sensory experience and the adaptive, intuitive feedback sets this apart from neurofeedback games that simply levitate a ball or race a car [29] or are exclusively auditory [30].

To date, the system has only been used in an interactive installation at the Asian Art Museum of San Francisco until its closure due to the COVID-19 pandemic (January to March 2020). The details of this project are described in separate manuscript [31]. The formal testing of the system is set to begin once campuses fully reopen and human studies are safe to conduct by IRB criteria.

Truly, the development of the *Mandala Flow State* proof-of-concept digital therapeutic would not have been possible in the absence of interest outside of this area of study. Primary funding for this work came from parties interested in the arts. Students and collaborators emerged from a diverse set of fields, none of which were in science or medicine. Major contributors studied computational creativity, industrial design, religion, music composition, theatre and art history. In the realization of the product—a neurofeedback platform that promotes user engagement and trains the brain towards the targeted goal—the talent and the tools present in the gaming industry became just as critical as the guiding science. This type of partnership is demonstrated by Deep VR and Gaming for Emotional and Mental Health (GEMH) Lab of Radbound University.

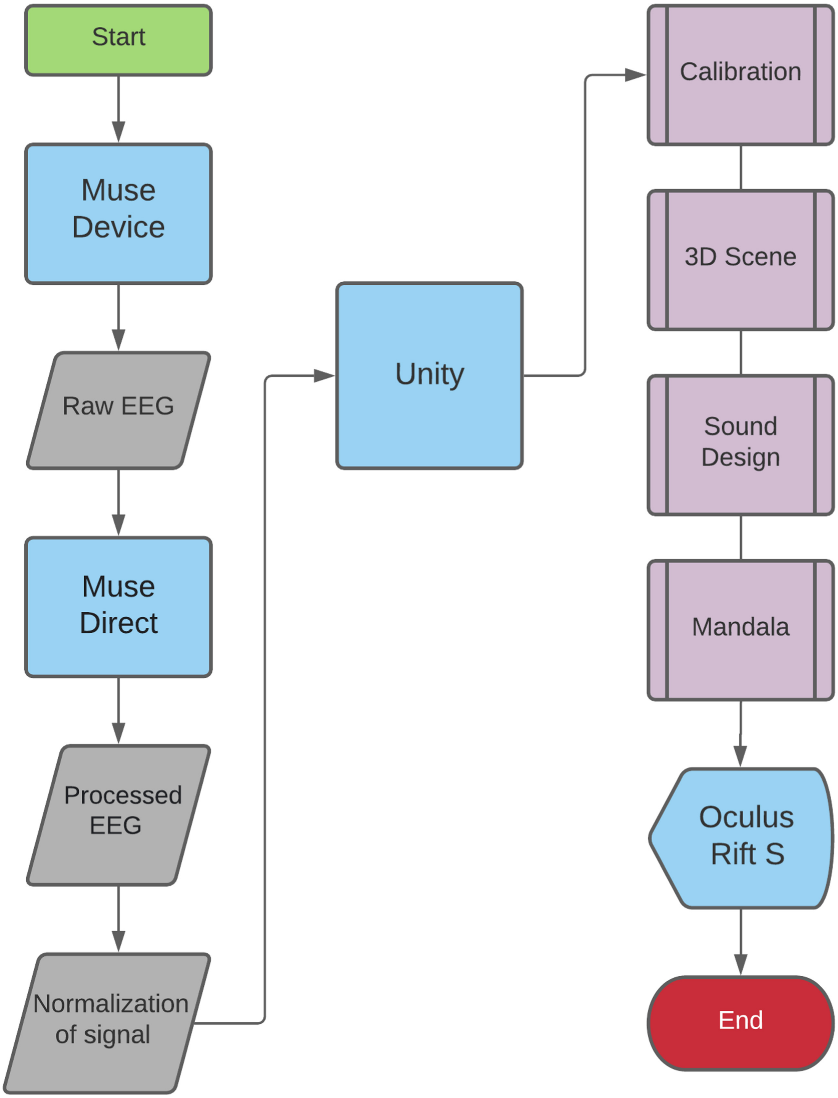

Fig. 3. *Mandala Flow State* workflow. Raw data from the Muse 2 device is read in by the Muse lab software where preprocessing to remove artifact and separate frequency bands is done. Then the absolute alpha power is output to our processing stream to be normalized and input as a control parameter in Unity. The VR display is a layering of the 3D scene, soundscape, the uniquely generated mandala and a fog filter. The alpha power inversely modulates the density of the fog in real time. That convergence is the output to the Oculus Rift S for the person to perceive. The user attempts to relax (or is relaxed by the experience) in order to increase the alpha power, our correlate of focused relaxation.

The product produced is a breathing pattern biofeedback meditative VR game aiming to treat anxiety [32]. The collaboration here led to numerous design and film awards for the

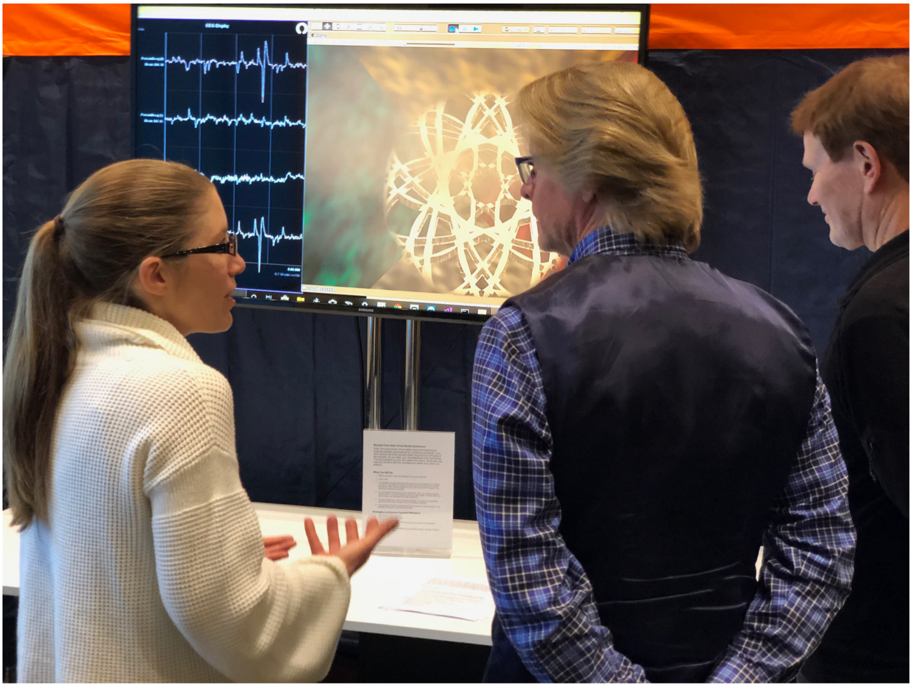

Fig. 4. *Mandala Flow State* at the Asian Art Museum of San Francisco. Inside of a tent, a participant was set up with the EEG band and VR headset try out the neurofeedback demonstration. The experience was mirrored to visitors as seen in the photo. To the left is the streaming EEG signal for each channel that is used to modulate the VR display, which is to the right.

VR game and scientific backing of the methods. Again, we see that equal contributions from professional game designers and the scientists are needed to achieve improved biofeedback therapies.

5 Challenges to VR Neurofeedback

The idea proposed presently is that a more immersive and richer environment afforded by VR will improve the neurofeedback training effects. The alternate effect may be just as likely. The greater complexity of the sensory input may overwhelm attentional systems and detract from the primary function of the game. Efficacy and user experience are yet to be comprehensively tested for any VR delivered neurofeedback construct. Naturally, this is the next step underway for *Mandala Flow State*. Acute effects of the experience will be evaluated by physiological measures of heart rate, heart rate variability, and breathing rate, and user self-report on scales of mood. Full training effects over the course of four weeks will include change in the State-Trait Anxiety Inventory (STAI), survey of perceived effects of the training. The outcome may also be dependent on the quality of the experience design: How well are directions given; Is the experience complex and uncoordinated or harmonious; Can users tolerate extended time in VR without tiring. These questions are yet to be answered by iterative experimentation and must be addressed prior to further investment into VR-based neurofeedback.

Another deterrent in the proposed system of a VR platform for neurofeedback games is the adoption of VR technology broadly. At this time, only 14% (or fewer) of households in the USA have VR headsets [33]. These devices must be paired with "gaming" computers for the sake of the processing speed and graphics card specifications. The current technical requirements of a VR system may make the proposed neurofeedback training out-of-reach for many. However, as progress is made with stand-alone systems, like the Oculus Quest, and the wider use of VR games, more people may be open to adding on a brain training game or two. Game sales are 50% of VR software sales [34]. Again, the gaming industry supports the growth of the therapeutic use of BCI by driving growth in the market for VR. Further, if users are already familiar with BCI as a gaming modality, then the barrier to accepting neurofeedback games is lowered.

Lastly, exclusively EEG-controlled gaming experiences promise to be more intuitive. However, the lack of involvement of the body may counter this feeling. Naturally, we use our bodies to engage with the world. EEG signals are corrupted by the electrical activity of muscle movement, even facial expressions or head rotations. Imagine an excited player, who just achieved a milestone, couldn't express their victory outwardly. Improvements in real-time artifact detection and correction may mitigate these signal artifacts [35]. Unlike a research experiment, users should feel at home in the experience with freedom of movement and without pre-occupation of holding still. While excessive movement may add noise and degrade the detection of the desired pattern of brain activity, robust preprocessing and machine learning algorithms may make the system tolerant of them, thereby rescuing the neurofeedback loop [36]. Another strategy is to make use of both the controller and gestures in combination with the BCI to improve embodiment and engagement. This also allows for more dimensions of interaction with the game.

6 Conclusions

BCI is powerful framework with nearly endless applications [37]. The disciplines that use BCI are interdependent, as in the examples illustrated here. Integration of BCI in entertainment gaming gives a complementary push to therapeutic use of BCI. In particular, closed loop neurofeedback likens to the BCI game controller or modulator. Thus, any aspect of research or investment into BCI games simultaneously builds up the architecture for neurofeedback applications. Inadvertently, the adoption of BCI games in the future will create a ready market for brain training games. This is especially relevant for VR systems as the barrier to purchase said systems is greater.

The work done by our team is in the hope of changing the way neurobehavioral conditions are treated. When fully realized, it promises to give greater agency to the user in having control over their therapy. It reduces the dependency on clinicians and expands access to subclinical populations. By bringing the daily practice home and truly gamifying the therapy, patients for whom getting to the clinic is a challenge will be able to maintain therapy without interruption. What we imagine are adolescents and young adults, who are having difficulty managing their stress or maintaining focus, using the systems that they already have for entertainment and transforming them into therapeutic tool simply by choosing a new game.

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