# A Brain-Computer Interface and Augmented Reality Neurofeedback to Treat ADHD: A Virtual Telekinesis Approach

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**ABSTRACT**

Attention-Deficit/Hyperactivity Disorder or ADHD poses a severe concern for today's youth, especially when the costs, efficacy, side effects of medication and the lack of immediate risk discourage treatment. ADHD causes people to make impulsive decisions, making it harder to succeed in school, work, and other aspects of life. Neurofeedback Therapy has shown promising results as an alternative in treating mental disorders and improving cognition. It leverages the inherent mechanism of operant conditioning by presenting real-time feedback of the user's brainwave activity, which is usually acquired via an EEG. However, long sessions of monotonous feedback have proven tedious, and users lose motivation to continue. Engaging graphical interfaces and games have been developed to combat this issue and have been proven to improve the treatment's efficacy. In this work, we extend upon these methods to increase engagement by employing Augmented Reality in the context of a virtual telekinetic game. The system comprises three modules: an Emotiv headset for EEG acquisition, MATLAB for signal processing, and an AR mobile application to deliver the feedback. The hardware and software implementation, the signal processing methodology, and the Neurofeedback protocol are thoroughly outlined. Our next step is to conduct a pilot study with a subset of healthy children to evaluate the complexity of the process.

**Index Terms:** Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality; Applied computing—Law, social and behavioral sciences—Psychology

## 1 INTRODUCTION

Attention-Deficit/Hyperactivity Disorder (ADHD) is a prevalent neurological disorder that affects 5 to 10 percent of the world's children [31] and often persists into adulthood. The symptoms of ADHD include moderate to severe lack of attention, inability to control specific tasks, and high impulsive activity. These traits lead students to perform poorly in academics, and it has also been observed that when carried forth to adulthood, it can lead to involvement in crimes [8]. In developing countries, such disorders are not given the attention they require primarily due to the rising costs of medication and the lack of immediate risk [26].

Current evidence-based treatment modalities include medication, psychosocial/behavioral treatments, or both [6, 11]. Long term data from studies such as the Multimodal Treatment of ADHD (MTA) study, however, did not provide a clear answer about which approach bestows the best outcome in the long term [24, 27]. Research has also uncovered that drugs used to treat ADHD, such as Ritalin, Concerta, and Dexedrine, do not have any effect on certain children [22]. Moreover, parents are hesitant in accepting medication due to the side effects, which include the loss of appetite, anxiety, insomnia, headaches, and irritability. Dietary elimination, a non-drug treatment, also does not exhibit a notable influence on the majority of the patients [10].

Neurofeedback (NF) or Biofeedback is an alternative approach that allows users to rewire their brainwave patterns. Usually, a user cannot influence their brainwave patterns because they lack awareness of them. However, when they are provided with real-time feedback of their brainwave activity, they can regulate it through the mechanism of operant conditioning [13]. The brainwave activity is usually measured through Electroencephalography (EEG), which measures the minute electrical impulses in the brain produced when neurons generate action potentials. These EEG signals can be divided into five main frequency bands, each correlated with a particular cognitive function.

- Delta Waves (0.5 - 4 Hz): The Delta waves are produced when the mind is in a state of deep sleep.
- Theta Waves (4 - 8Hz): Theta waves are related to drowsiness. More recently, it has also been associated with learning, memory, and attention.
- Alpha Waves (8-12Hz): Generally, Alpha waves are associated with a relaxed mind. They are prominently observed in people whose eyes are closed.
- Beta Waves (12-30Hz): Beta waves are linked to emotional arousal and mental performance. Training to increase Beta band power can help ADHD patients who have problems with attention and hyperactivity.
- Gamma Waves (above 30Hz): Gamma waves are used as biomarkers to diagnose certain brain diseases.

Past research has shown promising outcomes in treating ADHD through EEG-based NF [20], and to produce measurable results in young participants, about eight to ten sessions are required [12]. This eventually leads to a decline in motivation for the patients undergoing the therapy, especially in children, and especially when the feedback they receive is not engaging enough [29]. The challenge we tackle in this paper is how to keep the users engaged while delivering effective NF. There has been a transition towards three-dimensional gamified interfaces in the past literature to combat this [34]. We aim to take this a step further by implementing Augmented Reality (AR) as a feedback medium. AR enables placing virtual objects in the real world seamlessly as though it appears as a part of reality. AR is more immersive, imaginative, and interactive than the traditional graphical interface, although it is not adequate if the content adopted is not stimulating enough.

Therefore for our work, we introduce a virtual telekinesis game, which involves transforming virtual objects by regulating brainwave patterns. By gamifying the feedback in this way, the treatment gets more engaging and entertaining, particularly for children, as it provides them with a sense of having superpowers. Two experiences were developed for telekinetic control: inflating a balloon, and bending a spoon. The size of the inflated balloon and the degree

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of bend of the spoon, serve as feedback, and are directly correlated with the user's psychological state. It has been shown that exercises, when hidden within gamified experiences, have helped children alleviate their concentration, control, and memory challenges [32]. More recently, the FDA approved the video game designed to treat ADHD, EndeavorRX[1], to be prescribed as a medical treatment.

The NF protocol implemented in this study, is the Individual Theta/Beta-1 ratio (TBR) training over the $C_z$ electrode (following the 10-20 international standard), one of the most commonly used paradigms in ADHD NF [22]. Studies have indicated that people with ADHD have relatively higher Theta activity and lesser Beta activity [14]. Hence, the aim is to decrease TBR by increasing the Beta-1 band power and lowering the Theta band power.

There have been several studies about using Virtual Reality (VR) in NF, but implementing AR in the context of a gamified telekinetic experience is not previously shown in the literature (to the best of our knowledge). Through a usability study, we aim to show that our system can keep users engaged over a more extended period while providing practical NF training. We hypothesize that Augmented Reality Neurofeedback will have a better efficacy and learning rate than the 2D interfaces used in clinical practices today.

## 2 Background

### 2.1 Neurofeedback Modalities

Neurofeedback was traditionally administered through auditory modalities, in which a particular sound would grow in volume or change its frequency depending on the brain wave activity. Hinterberger et al. [15] and Pham et al. [28] used ascending and descending pitches to represent amplitude shifts in Slow Cortical Potentials. Audio interfaces are still in use today, Sajda et al. [9] implement a heartbeat rhythm, whose thumping grows louder if the subject is not attentive to the task at hand.

Interesting benefits of vibrotactile feedback were documented by Cincotti et al. [7], primarily used because the subjects were performing complex visual tasks. Neuper et al. [25] also point to evidence of rich visual feedback facilitating learning, as in three-dimensional video games or VR environments. In our interface, audio feedback is implemented to help users differentiate between positive and negative feedback. This is particularly helpful when the change in feedback is minute and not visually prominent.

### 2.2 Neurofeedback through Graphical Interfaces

One of the earliest works of using graphical interfaces for ADHD intervention is by Miles et al. [23], where the Beta/Theta ratio was used as an input to a flight simulation game. The Beta/Theta ratio controls the plane's height, and the goal was to reach a destination while avoiding obstacles along the way.

Yan et al. [33] also implement a graphical environment for NF training of attention. The signal from electrode $C_z$ was processed to obtain the TBR, and the signal from electrodes $Fp_1$ and $Fp_2$ were processed to obtain the Sensorimotor Rhythm (12-15Hz) band power. These parameters control a spaceship's speed via a graphical interface and is vaguely similar to our work's telekinesis approach. However, it lacks the realism and immersiveness possible with AR. A study of 12 subjects with ADHD after 20 NFT sessions (each session being 25-30 minutes) revealed a significant improvement in attention. The subjects also claimed that the 3D environment was more interesting than the 2D games used in a previous system.

*Harvest challenge*, a video game developed by Blandón et al. [4] is driven by players' attention levels, measured by a commercial low cost EEG sensor - Mindwave. The attention levels acquired from the TBR are mapped from 0 to 100 and are explicitly visible to the users. The player begins by collecting equipment needed for a canopy ride, which is done by increasing the attention level to 50 percent. A study was conducted with 9 ADHD-diagnosed children who played the game for two sessions, each session being 30 minutes long. A multilinear regression model revealed that the Theta band (of all other bands) had a significant impact on the game's progress. Overall, there was an improvement in the participant's attention levels, analyzed from the game metrics.

The TBR is measured individually with an Emotiv headset by Liu et al. [19] in their NF study to improve cognition. They developed a shooting game in which the user's brain activity determines the target's color. When the color turns from blue to red, the user is in the right mind state and can shoot the target. The Individual Alpha Peak Frequency (IAPF) and the Individual Alpha Bandwidth (IABW) is determined from a one-minute eye closed, and eye open recording [2, 3], and from which the Theta, upper Alpha, and Beta ranges are extracted. Our work also utilizes the said algorithm to estimate the individual parameters. The TBR is compared against a threshold (average TBR during resting), and accordingly, the feedback is delivered in the game. An analysis was carried out with five subjects who underwent 40 minutes of training. Four subjects exhibited an increase in the IAPF, although the fifth subject who already had a high IAPF exhibited an increase in the IABW.

Mandryk et al. [21] developed a novel framework that makes it possible to adapt any off-the-shelf computer game into an NF system. They do this by displaying visual artifacts on the screen when the user is not in the desired psychological state, which blocks the user's view and hence, affects gameplay. Moreover, the textures of these graphical overlays can be customized to individual games, delivering a more consistent and integrated experience. Although not explicitly related to our work, the system shows great potential to be used in NF.

### 2.3 Neurofeedback through Virtual Environments

*RelaWorld*, developed by Kosunen et al. [18], is a VR NFT in the context to help users enhance their mindfulness through meditation. The system placed users on a tropical island, where they can levitate if they are in the desired psychological state. An energy bubble surrounds the user and becomes opaque as the user relaxes. Data from the Alpha and Theta band powers over six electrodes influence the floating and the opacity of the bubble, respectively. A user study of 43 subjects revealed that the system running on a VR HMD generated higher meditative states than when displayed on a standard screen.

AR Sandboxes have also been used to improve mindfulness via NF, such as the *Inner Garden* by Roo et al. [30]. The garden's elements are connected to physiological measurements taken from the user, such as breathing and heart rate. The breathing patterns are mapped to the water levels that create waves, and the heart rate is mapped to the number of clouds, the flora's growth rate, and the sounds from the fauna. Users can also visit the garden designed by them, in VR by placing a mini-avatar in the sandbox. A preliminary user study of 12 participants revealed that the system cultivated a calmer state of mind and improved mindfulness. However, it is a cumbersome set-up, and hence not as portable as our approach.

Another novel form of feedback was implemented by Cavazza et al. [5], where they integrate virtual agents into a VR environment that react according to a predetermined storyline. It follows a medical drama genre and features a female doctor who is facing difficulties in her life. By expressing positive thoughts, the user can help the character, and should they succeed, the narrative will evolve in favor of the character. Band powers have not been the only paradigm used in NF for ADHD. Ali et al. [1] implement the Steady State Visually Evoked Potentials paradigm in a VR classroom setting, where the goal is to concentrate on 2D games on the blackboard while avoiding distractions.

Our work extends these types of NF modalities by employing a novel gamified Augmented Reality experience, making NFT a

[1] https://www.akiliinteractive.com/get-endeavor

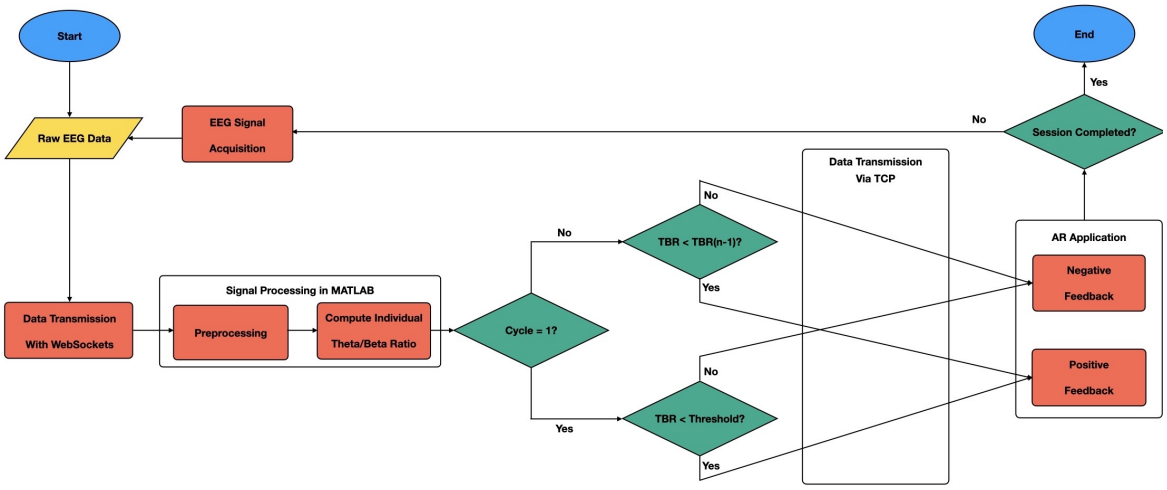



Figure 1: Overview of the system architecture.

more compelling, interactive, and imaginative experience. To the best of our knowledge, an AR Neurofeedback system in the context of gamified telekinetic experience is not previously shown in the literature.

## 3 Virtual Telekinesis Approach

Combining EEG and AR presented us with multiple technical hurdles. First, the classified EEG data must be sent over a network in real-time to the AR application. Second, the signal has to be corrected for noise and artifacts from head-movement and eye-blinks.

Our system consists of three main modules: an Emotiv EEG headset, a system running a MATLAB script, and an AR application running on a tablet. The data flow is as visualized in Figure 1. The raw EEG data acquired by the Emotiv headset is streamed to the system through a WebSocket connection, where the MATLAB script parses the data as a time-series signal. After the signal is preprocessed, classified, and the features extracted, the relevant data is relayed to the AR application via TCP packets. Upon receiving this data, the AR application provides the user with positive or negative feedback.

### 3.1 EEG Acquisition

The 14-channel Emotiv Epoc, with a sampling rate of 128 Hz, is used to acquire the raw EEG signals. We chose the Epoc primarily for its simplicity, wireless connectivity, and quicker set up times. The raw EEG data is streamed over a WebSocket connection to a system on the local network. MATLAB running on this local system receives the data, accumulates it for 5 seconds, and then processes it. The 5-second wait is to provide the user ample time to react to the previous feedback. Post the wait, there is a negligible latency of ~62ms (processing time) until the user recieves the feedback.

### 3.2 Signal Processing

Due to the intra-variability of spectral bands between individuals caused by age differences [17], an individually adjusted frequency algorithm [19], is adopted in this study. Not accounting for such individual differences has been proved ineffective and also leads to undesired clinical effects [16]. Before administering the NFT, the initial parameters like the IAPF, IABW, and the spectral boundaries of Theta and Beta-1 (referred to as Beta hereafter) band need to be established. Hence, we perform a baseline evaluation where the subject's one-minute eye closed and one-minute eye open resting-state EEG are recorded.

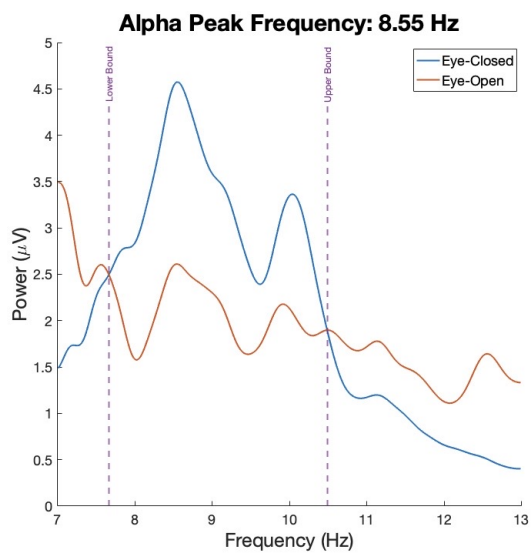
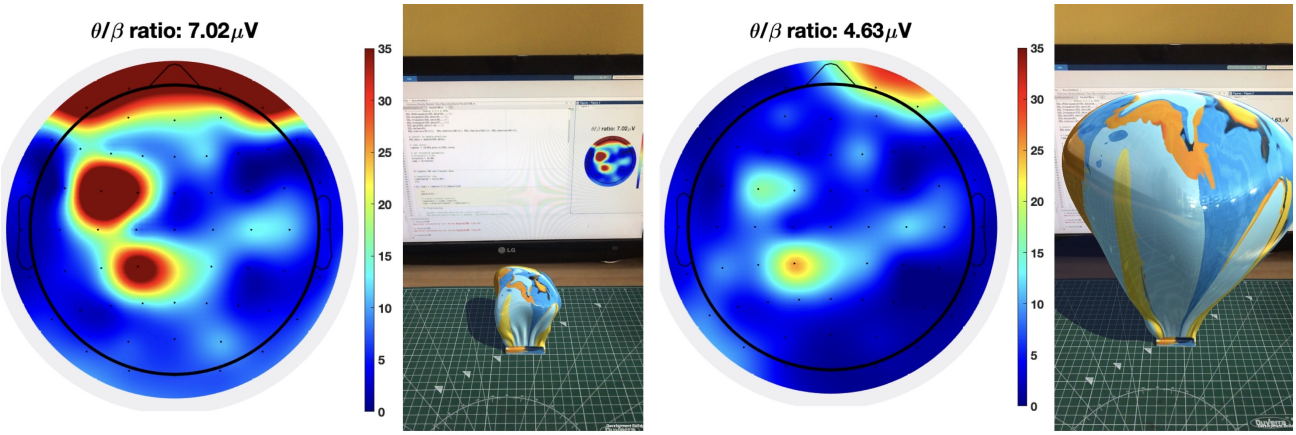



Figure 2: Power spectral densities of the eye-closed and eye-open resting states are plotted. The dotted lines represent the IABW, interpreted as the intersection points of the two plots.

The IAPF is determined as the peak frequency in the eye-closed EEG, and the IABW is defined as the frequency range suppressed when the eye-closed and eye-open EEG are compared [2], since the Alpha band is suppressed when the eyes are open. As seen in Figure 2, the blue curve is the eye-closed EEG and the orange curve, the eye-open EEG. The maxima of the blue curve denote the IAPF, and the point of intersection of the curves on the left side is established as the lower Alpha boundary and on the right side, the upper Alpha boundary. As stated by [2], the Theta band extends from 3 Hz to the lower Alpha boundary, and the Beta band extends from the upper Alpha boundary to 18 Hz. The $C_z$ electrode's individually-adjusted band powers, from the eye-open resting state, are averaged over the specified ranges, and the computed TBR is set as the threshold.

During NFT, the signal from channel $C_z$ is identified and preprocessed to remove artifacts. The time-series signal is demeaned, and




(a) (b)

Figure 3: The (a) topography map of the Theta-Beta ratio (TBR) and the balloon size of a particular cycle, compared to the (b) topography map of the ensuing cycle's TBR and its balloon size.

filtered with a low-pass FIR filter of 22Hz. The Fourier Transform to convert the signal from the time-domain to the frequency domain is computed using Welch's method as it is capable of reducing the non-systematic noise variance in the power spectrum and smoothing out the non-stationarities characteristic of an EEG signal. More specifically, we used the pwelch function from MATLAB's Signal Processing Toolbox. The taper is a Hann window, with a window size of 1.5 seconds and an overlap of 25 percent. Furthermore, zero-padding is applied to increase the spectral resolution.

The Theta and Beta band powers are extracted over the specified ranges and are averaged to compute the TBR. For the first cycle, the ratio is compared to the threshold ratio computed during the baseline evaluation. If it is found to be lower than the threshold, positive feedback is delivered, and vice versa. For subsequent cycles, the feedback is dependent on the percentage of the current cycle's ratio to the previous cycle's ratio, making it adaptive. In Figure 3, the TBR and the balloon of a particular cycle can be seen compared to the ensuing cycle's TBR and its balloon. As shown, when the TBR reduces from $7.02\mu$V to $4.63\mu$V, positive feedback is delivered by inflating the balloon.

### 3.3 Augmented Reality

Meticulously crafted AR experiences are indistinguishable from reality itself and are what we sought to achieve in this work. The three-dimensional model of the balloon and the spoon, along with their animations, were designed in the 3D modeling software Cinema 4D[2] and imported in point caches to the Unity[3] game engine, where the AR experience was developed. We used Cinema 4D's Soft Body Dynamics feature to compose the balloon animation and provide the object with the corresponding physics. At first, the animations were exported using the Alembic format, but it was later switched to point caches as it was not supported on mobile platforms. The *Point Cache Player*, from the *Vertex Animation Tool*[4], was used to seamlessly animate the point caches.

The application's SLAM and plane tracking capabilities were provided by Unity's ARFoundation[5] class, which abstracts the ARCore or ARKit SDK, depending on whether an Android or iOS application is built. The virtual objects are instantiated on a flat surface in front of the user. Real-time shadows, environmental light estimation, and reflections generated by Unity's reflection probes are employed to make the content as realistic as possible. The consensus was that the more photorealistic the virtual content seemed, the greater it would enhance the experience and ergo improve the NF efficacy. When there were minor changes in the feedback, it was challenging to ascertain whether it was positive or negative; Hence, audio cues were included to help the user distinguish between them. As shown in Figure 4, Textual feedback in the form of motivational phrases were also included to encourage users if they performed poorly, and if they did exceptionally well. Please also refer to the video demo in the supplementary files, recorded from the AR application.

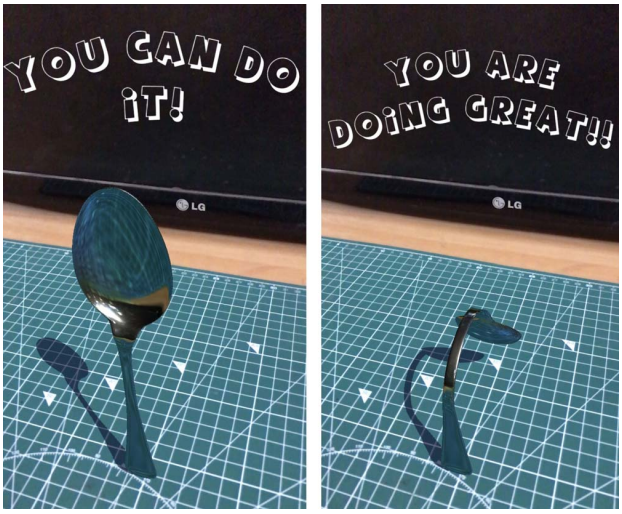



Figure 4: The textual feedback is presented on the screen space. The environment's reflections on the virtual spoon are also evident.

[2]https://www.maxon.net/en-us/products/cinema-4d/overview/
[3]https://unity.com/products/unity-platform
[4]https://assetstore.unity.com/packages/tools/animation/vertex-animation-tools-128190
[5]https://unity.com/unity/features/arfoundation

### 3.4 Neurofeedback Protocol

Neurofeedback is being used to improve cognition and treat mental disorders for a long time now, and several studies and Randomized Controlled Trials have proven its clinical efficacy in improving the mental state. The nature of the NFT implemented in this study is based on Baseline Increments, where the learning is manifested through the pre-training EEG baselines of successive sessions [12]. Many training protocols are used in treating ADHD, such as Alpha Peak Frequency, Slow Cortical Potentials, Theta-Beta ratio, and the Sensorimotor Rhythm training. The Alpha band is easily susceptible to artifacts caused by eye blinks, and hence we did not favor it. We preferred the Theta/Beta ratio protocol due to its higher prominence in the ADHD NF literature.

We intend to conduct a pilot study, first with healthy children, and followed by children diagnosed with ADHD. A baseline evaluation will be conducted prior to every session, which includes measuring the IAPF, IABW, followed by the threshold TBR. The significant increase in the resting-state threshold TBR, before and after the intervention, will corroborate the systems' efficacy. To know if the approach had a successful impact on the child's motivation to complete the therapy, a control group with a traditional two-dimensional feedback will also be evaluated.

## 4 Conclusion

In this work, we aimed to create an interface to improve the efficacy and learning rate of Neurofeedback Therapy by employing an immersive, interactive, and imaginative feedback medium via Augmented Reality. We were successful in developing an AR telekinetic game to treat ADHD, where the user can inflate a virtual balloon, or bend a virtual spoon by reaching the desired psychological state. We believe this interface will particularly motivate children to undergo and complete the therapy, as it provides them with the sense of having superpowers. The system adopted the commonly used ADHD Neurofeedback protocol to reduce the Theta/Beta-1 ratio by increasing the Beta-1 band power while concurrently decreasing the Theta band power. For future work, we plan on improving the preprocessing of the EEG signal by implementing adaptive filtering, which will be more effective at removing artifacts. Our next step is to assess the efficacy of the system with a subset of healthy children followed by children diagnosed with ADHD. We hypothesize that Augmented Reality Neurofeedback will result in a better efficacy than the 2D interfaces used in clinical practices today. We wish to employ this technique in various other NFTs and develop more interactive gamified content in the future. We believe that as a result of this non-pharmacological intervention, parents will be more inclined to get their children treated for ADHD.

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