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Impact of Brainwave Entrainment using VR to Improve Attentional Learning in Children with ADHD, ASD and Comorbidity

Manasa Mandapati*, Prabhat Ranjan
DY Patil Pratishthan, School of Interdisciplinary Studies and Reasearch, DYPIU, Pune, 411044, India
Email(s): prof.prabhat.ranjan@gmail.com (P. Ranjan)
*Corresponding author: Manasa Mandapati, DYPIU, Contact No & Email: manasa.mandapati@gmail.com

ABSTRACT: Various neurological disorders (NDs) across the globe are prevalent among children, affecting their quality of life. Among them are Attention Deficit Hyperactivity Disorder (ADHD), Autism Spectrum Disorder (ASD), and comorbid conditions, which are defined by proximity of symptoms of inattention, hyperactivity, and impulsivity that are accompanied by impairment in several functional domains. The overall aim of this research is to improve attentional learning in children with NDs using brainwave entrainment techniques with cutting-edge technology like virtual reality and artificial intelligence. For photic stimulation, pulses of light (virtual reality device) were used. For audio stimulation, binaural beats (noise-cancellation headphones) were used. We identified 40 children in the age group of 6 to 12 years, diagnosed by clinicians as ADHD or ASD, or comorbid conditions. Among 40, Audio Visual Entrainment (AVE) at 10 Hz frequency was administered to 23 subjects for 20 days, with 15 minutes daily. Electroencephalogram (EEG) signals were recorded before and after stimulation using the Emotiv Epoc X device. Initially, the data was pre-processed using the Welch method and independent component analysis (programming done in Python and MATLAB). The power spectral density and the relative band power ratios were calculated. The data was analyzed using quantitative analysis, which included comparative and statistical analysis. This analysis revealed a reduction in distraction and an improvement in cognition and attention among subjects with ADHD and comorbid conditions. No improvement was observed in ASD subjects. A positive result is observed in 72% of the ADHD subjects and 66% of the comorbidity subjects, with only 16% of ASD subjects.

KEYWORDS: Electroencephalography, virtual reality, Independent component analysis, brainwave entrainment, photic entrainment, ADHD, Autism Spectrum Disorder, Comorbid

1. Introduction

Lack of attention due to neural disorders (NDs) impacts children's learning ability, communication, and behavior. Attention Deficit hyperactivity disorder (ADHD), Autism Spectrum Disorder (ASD), and comorbid conditions are the most common NDs among children [1]. According to the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) (2013) [2], the children with ADHD

- Suffer from lack of attention,
- Regularly does not follow the instructions,
- Gets distracted very easily by extraneous stimuli in the envithe environmentd
- Usually forgets the daily activities.

They avoid tasks that need to sustain mental efforts and have difficulty completing problem solving tasks that require attention. A study by PilaNemutSandani [3] concluded that participants with ADHD had poor organizational and planning skills. The difficulties with executive functioning and complex reasoning is one of the reasons to believe that people with ADHD lack problem-solving skills [4].

A substantial minority of children with ADHD demonstrate ASD symptoms [5, 6]. ADHD is the most common comorbidity in children with ASD at a range of 40-70% [7, 8, 9, 10]. Consistent with the data, some researchers assert that although ADHD symptoms occur without ASD symptoms, ASD symptoms do not occur without ADHD symptoms. Most children with ASD had high levels of inattention and hyperactivity, thus introducing bias into ADHD diagnosis. The co-occurrence of the symptoms [6] made comorbidity research important in this field.

ASD is a behavioral syndrome with impairments in several areas of development including social interaction, communication, and stereotypical interests and activities (American Psychiatric Association, 2013 [2]). Autism can affect either the intelligence quotient (IQ) continuum, or the level of language function by age six [11]. These are strong predictors of clinical outcomes. Autism is invariably accompanied by language delay. People with Asperger syndrome (AS) and autism have common symptoms like social impairments and restricted behaviors. However, their verbal and nonverbal IQ will be average or above, without serious language impairment [12]. The most common treatment for ADHD is through psychostimulants such as Ritalin and Adderall which have short-term positive effects and/or severe long-term side effects [13, 14]. An

alternative to ADHD medication is brainwave entrainment, a method that naturally synchronizes the brainwaves to external periodic stimuli.

The brain can change under the influence of experience, as well as restore lost connections after damage or as a response to external influences [15] as per the phenomenon of neuroplasticity. This phenomenon can be used to develop memory, learning, attention and restore damaged cells [15]. Studies illustrate that the central nervous system was developed in a predictable sequence [15]. First is the development of senses, second is the movement/motor, and third is the mental/cognitive ability. To better understand the nature of sound/light of the first language, it would be simple to consider first language expression as music and light. Appreciating the potential of deeply rooted sensory communications that do not rely on higher cognition characteristics of mental processing, the signal approaches can be considered positive [16]. This signaling can be presented in light and sound compositional designs that permit the brain to shift in and out of degrees of stable/unstable behaviors. Studies also illustrate that light and sound brain engagement can guide the brain into beautiful positive neuroplasticity experiences [17].

There are different methods to acquire brainwave entrainment. In this research audio visual entrainment using the pulses of light and the binaural beats were chosen. Visual entrainment was done using periodic sinusoidal light pulses in a Virtual Reality (VR) environment [18, 19, 20, 21]. Photic stimulation of 10 Hz was well known to entrain the EEG signals in human beings [22] as it helps to relax the brain and improve the rewiring of cognitive styles and communicative patterns. Alpha rhythm exerts beneficial effects on cognition and behavior [23, 24, 25, 26, 27, 28, 29]. Therefore, the alpha frequency was used in the present study. Furthermore, findings from studies state that differences in working memory load have been linked to modulations in theta peaks, along with the theoretical and empirical support of the role of theta-gamma phase coupling in STM/WM capacity [30]. This suggests that the individual differences in theta frequencies (and gamma frequencies) could potentially be linked to individual differences in WM or STM capacity [31]. Binaural beats were provided using a lower frequency tone in one ear and a higher frequency tone in another ear using headphones, the superposition of these two waves of different frequencies produces a beat wave to which the brain gets synchronized [32, 33].

A single cell recording studies and neurological studies state that social intelligence was a function of three regions: the amygdala, orbitofrontal, and medial frontal cortices in which abnormalities in autism have been found. Studies in neuroimaging have implicated the Prefrontal cortex in attentional functions, in ADHD [14]. Understanding the cognitive behavior of the brain can be done using the signals or images from the brain [34]. Thus, EEG signals were captured using a consumer-grade portable 14-channel EEG device, Emotiv Epoc X, in this research to study the changes that occurred before and after the brainwave entrainment. The overall aim of this research is to improve attentional learning in children with NDs using brainwave entrainment.

2. Related Work

The change in the neural structure and function in response to experience or environmental stimuli is called neuroplasticity. Considerable changes in the brain's anatomical structure and connectivity occur during childhood [35, 36, 37]. Studies indicate that functional parcellation of cerebral cortical areas into discrete processing centers involves a wide range of signals with tangled interaction, between mechanisms both intrinsic to cortical progenitors and neurons and environmental stimuli extrinsic to the cortex which require neural activity such as light stimulation to the developing eye [38].

ADHD is one of the most heritable neuropsychiatric disorders [39, 40]. EEG recordings reveal that ADHD children produce more theta (4-7 Hz) wave activity in the brains frontal and central cortical regions [41]. ADHD children also produce less beta (13-21 Hz) wave activity [42]. Changing the cerebral electrical activity associated with ADHD has improved ADHD children's symptoms [42, 43, 44]. As an alternative treatment approach to ADHD, neurofeedback has been used to increase cerebral activity [42, 45, 46, 47, 48].

Before the DSM-5 [49] in 2013, clinicians were unable to make an ADHD diagnosis in the context of ASD. It was presumed that any symptoms of inattention and/or hyperactivity-impulsivity were secondary to ASD and not due to an additional ADHD diagnosis [50]. ASD and ADHD often co-occur [51]. Hyperactive, impulsive symptoms correlate strongly with restricted and repetitive behaviors in ASD [52] and family members of individuals with ASD have elevated rates of ADHD diagnoses [53, 54, 55] and vice versa [56].

Many researchers are testing the therapeutic effectiveness of Audio-Visual Entrainment (AVE) as a treatment for a variety of low-arousal brain disorders like ADHD. AVE is the repetitive and intermittent presentation of light and sound. AVE affects the EEG output [23, 57, 58, 59, 60, 61, 62, 63]. It has been suggested that many clinicians are using AVE informally for ADHD with anecdotal reports of successful treatment but with few published results [64, 65]. Researchers [66] conducted a pilot study using AVE to treat learning and behavioral disorders. Russell states that AVE achieves the same results as EEG biofeedback but at less cost and in less time [44]. Due to tremendous changes in technology, hardware, and software, there is a need to expand the research. A study on augmented cognition via brainwave entrainment in virtual reality by Argento E, Papagiannakis G, and his team proved a concept that the theoretical idea of fast learning in VR under certain conditions is indeed feasible and has important practical potential [67]. Nowadays, all kinds of technologies in the VR field are developing rapidly. Recently VR has been used for brainwave entrainment in many researches but they were used only in place of tasks to be done during entrainment and EEG data was not considered [68, 69, 70, 71].

Brief, intense flashes produce harmonic activity in the brain [21]; whereas, sine wave stimulation produces a sine-like response (insignificant harmonic activity). Researchers [18, 19, 20, 21] agree that sine-wave modulated light eliminates the problem of light intensity from a Xenon strobe

increasing with frequency and the harmonics generated within the neo-cortex at frequency multiples much higher than the fundamental at times. The raw EEGs shown in the studies, show neither signs of epileptiform activity nor any discussion about it. To address the concerns of eliciting a photic-induced seizure, the VR device video used had a slowed turn-on and -off time of about 15 msec. The light emitted from the VR device was white.

The purpose of this research was to expand the research on learning disorders and to further determine the effectiveness of AVE in reducing the symptoms associated with learning disorders by introducing new technologies and software for entrainment and data collection. The research also contributes in finding tremendous potential and usability of VR in brainwave entrainment.

3. Materials and methods

3.1. Ethical clearance

The methodology used in this research was approved and performed following the guidelines and regulations approved by the institutional ethics committee. The parents/legal guardians of all the participants signed the consent forms. The study took place from November 2022 to November 2023 in a separate room in a children's school environment under the observation of the researcher. Consumables like sanitizers, masks, and tissues were used as per COVID protocols. The study was accomplished using protocols established by the foremost clinicians and researchers in the field.

3.2. Data Collection

We approached approximately 200 subjects, among which 110 parents declined or were not interested to participate in the research. 90 subjects parents/legal guardians accepted to participate but only 33 finally met the inclusion and exclusion criteria and gave the consent to participate in the research. However eventually, only 23 subjects completed all the sessions including pretest survey.
Inclusion criteria

- Subjects in the age group of 6-12 years
- Clinically diagnosed: ADHD, ASD, COMORBID
- Gender eligible for study: All
- Socioeconomic background: All
- Parents/Legal guardians and subjects willing and able to give consent for taking part in the research study

Exclusion criteria

Since visual brainwave entrainment can stimulate large areas of the brain, certain people listed below should not use this technology. Those who have

- History of seizures, (especially epileptics)
- History of brain injury
- Hearing-related disease
- Any known ocular disease in one or two eyes

EEG signals were recorded before and after sessions from the 23 subjects, and demographic information of the subjects is summarized in Table 1 and Table 2. In the pretest survey, data on the diagnosis of a disorder by clinicians (pediatricians/neurologists/psychiatrists), age, sex, left or right-handed, and verification of medical diagnosis report were obtained. Based on the pretest survey, the data was subdivided into three groups. This experiment does not require a traditional control group. In the study, we compared individual A's pre-session data with the post-session data of individual A i.e. when AVE does not influence the participant and when AVE influences the participant. Thus pre sessions data is equivalent to control group.

Table 1: Demographic data of the subjects who participated in the research

S.No.	Data	No. of subjects
1	Subjects	23
2	Male	19
3	Female	4
4	Avg. age	8 years
5	LH	2
6	RH	21

Table 2: Classifications of the subjectsbased on the clinical history

S.No.	Diagnosis	No. of Subjects
1	ADHD	11
2	ASD	6
3	Comorbid	6

3.3. Device Information

The following devices were used in this research Hardware

- Emotiv Epoc X -14 channel wireless EEG headset to record the brain activity.
- Noise cancellation headphones for audio entrainment.
- Oculus Quest 2 VR headset for photic entrainment.

Software

- Emotiv Pro Suite v3.2.1 can be downloaded from https://www.emotiv.com/products/emotivpro to obtain the raw EEG data.
- Matlab 2022b from Math Works Incorporation at https://in.mathworks.com , and Python v3.33 for data analysis.
- Audacity v3.2.1 which can be downloaded from https://www.audacityteam.org for generating binaural beats.
- Adobe Premiere Pro 2020 from https://www.adobe.com/in/products/premiere.html for generating pulses of light in VR.

The software used is installed on a personal computer with the following specifications: Intel(R) Core(TM) i3-8130U CPU @ 2.20GHz 2.20 GHz, and 8 GB in RAM. The Emotiv Epoc x is paired to the system via Bluetooth and the EEG data was monitored and recorded in Emotive Pro Suite.

3.4. EEG data recording

EEG readings were recorded in the subject's school environment using 14 Ag/AgCl electrodes (AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4) and 2 references CMS/DRL references at P3/P4. These electrodes were positioned according to the 10-20 international system with the bipolar method. This system is a standard system of positioning the electrodes for reliable data comparison across all the laboratories in the world.

Entrainment is given with eyes open in a VR environment at resting condition under 10 Hz photic stimulation (white light) with brightness intensity of 200 cd/m2 along with audio stimulation using binaural beats at 10 Hz for 20 days with 15 minutes per day. The pulses of light are imposed on a video made of pictures of birds and animals. A total of 20 min EEG signals pre and post-stimulation sessions were obtained. These EEG signals were sampled at the rate of 128sps and 14-bit resolution. In addition, the signals were recorded in ASCII format.

3.5. Methodology

The block diagram of the proposed methodology is depicted in Fig. 1. Initial screening of participants took place to identify the relevant subjects and pretest was conducted. Once subjects were identified and consent was signed, initial EEG data was recorded. From the next day, entrainment sessions took place for 20 days. On the 21st day, the final EEG data was recorded. After data collection data analysis was done and the results were discussed in the results section.

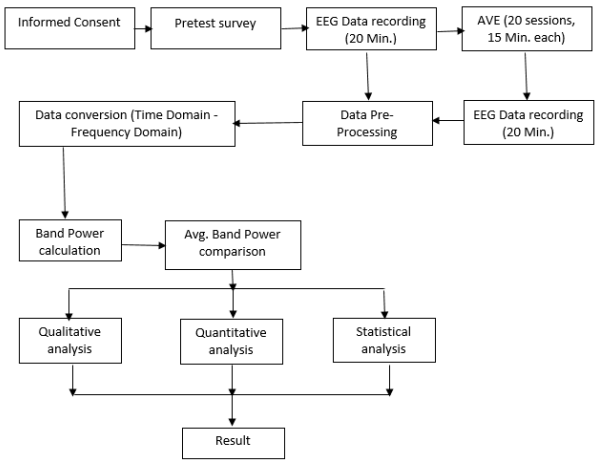

Figure 1: The block diagram of the methodology

3.5.1. AVE Sessions

Initially, EEG signals were recorded from the subjects before entrainment sessions. Then a combination of audio and photic stimulation at 10Hz (white light with intensity 200 cd/m2) with eyes open was given for 20 days (15 minutes per day). Later, EEG signals were recorded post-sessions with a sampling rate of 128sps at 14-bit resolution.

3.5.2. Data Processing

The Emotive software gives the recordings in a .csv file and edf file. Steps during data pre-processing were reading the signal stream as well as event timing information along with electrode positions, followed by filtering (0.2–12 Hz band-pass filter with Hamming window and a transition bandwidth of 4 Hz), relevant electrode selection (FC5 and FC6), discretization into epochs (from 0 until +900 msec after stimulus onset), application of Independent Component Analysis (ICA) and hybrid artifacts rejection methods (improbable data epochs of amplitudes over 25 micro V, abnormal data trends, abnormal frequency spectrum amplitudes of over ±25 dB, values higher/lower than 8 standard deviations of the data amplitude distribution, as well as visual signal inspection) followed by the calculation of grand averages across all of the epochs.

ICA has been proven to be more effective and flexible in separating EEG signals from artifacts. ICA is a linear model that decomposes the acquired sensor data into components that can subsequently be interpreted regarding the underlying physiological processes (e.g. brain, eyes, muscle, other). The effectiveness of ICA is given in a study conducted by [72]. In contrast to traditional artifact removal algorithms, various authors tested the independent component analysis (ICA) method on simulated and experimental data and showed good performance in the separation of signals from their linear mixtures and the extraction of eye information present in EEG signals [73, 74, 75]. To avoid errors introduced by manually selected components, automatic extraction and removal of eye movement artifacts were introduced after ICA analysis [76].

Band Power Separation: In EEG signal processing, separating the power spectrum density into the following bands is common. Delta (1–4 Hz), Theta (4–8 Hz), Alpha (8–12 Hz), Beta (12–25 Hz), and Gamma (25–40 Hz) using Welch method in which FFT was used with the moving Hanning window. The data is divided into K overlapping segments of length L. The Hanning window was enforced for each section. FFT was calculated in each window and PSD was computed as an average of FFTs over all windows [77]. One downside to the compactness of the headset concerning our paradigm was the lack of a Cz electrode, which would have been especially suitable for recording errors due to its proximity to the ACC, so our study focused on its two nearest available electrodes, FC5 and FC6.

The band power ratios were calculated using Eq. (1) to (9).

$$RelativeThetaPowerRT \quad {}^{n}_{i1}\Theta_i T\, xreturn \tag{1}$$

$$RelativeThetaPowerRT \quad {}^{n}_{i1}\Theta_i T \tag{2}$$

$$RelativeAlphaPowerRA \quad {}^{n}_{i1}\alpha_i T \tag{3}$$

$$RelativeBetaPowerRB \quad {}^{n}_{i1}\beta_i T \tag{4}$$

$$ThetatoBetaRatioTBR \quad {}^{n}_{i1}\Theta_i \, {}^{n}_{i1}\beta_i \tag{5}$$

$$ThetatoAlphaRatioTAR \quad {}^{n}_{i1}\Theta_i \, {}^{n}_{i1}\alpha_i \tag{6}$$

$$ThetatoAlpha \;\; BetaRatioTABR \quad {}^{n}_{i1}\Theta_i \, {}^{n}_{i1}\alpha_i \;\; \beta_i \tag{7}$$

$$BetatoAlpha \;\; ThetaBAT \quad {}^{n}_{i1}\beta_i \, {}^{n}_{i1}\Theta_i \;\; \alpha_i \tag{8}$$

$$TotalPowerT \quad {}^{n}_{i1}\Theta_i \;\; \alpha_i \;\; \beta_i \tag{9}$$

where n is the channel number,
β l = Beta low
β h = Beta high.

After calculating all the band powers and band power ratios, the values obtained before and after AVE sessions were compared and the data analysis was done. Data normalization was done using MinMax scalar and fit transform was used to fit the data and then transform the data. The amplitude spectrum of data was plotted in Fig. 2 and PSD was plotted in Fig. 3.

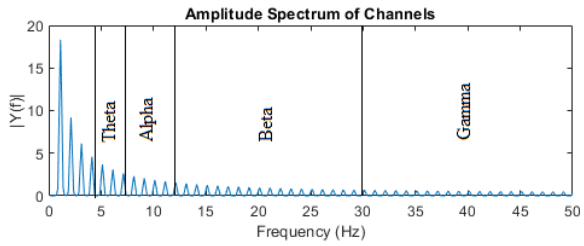

Figure 2: Amplitude spectrum of the data of ADHD subject 2

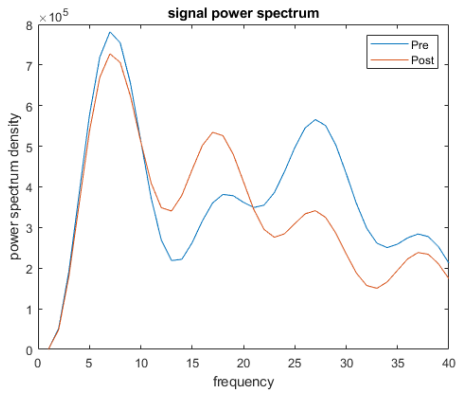

Figure 3: Power spectrum of the data of ADHD subject 2

The PSD in Fig. 3 indicates that the Theta frequency (4-8 Hz) was suppressed and Beta low frequency (12-18 Hz) was invoked. Increased beta levels to theta and alpha indicate improvement in attention levels.

4. Data Analysis

Initially based on the clinical data, the subjects were subdivided into three categories ADHD, ASD, and Comorbid. To understand the brain activity of the subject, the EEG data from front central electrodes FC5 and FC6 was computed before and after the AVE sessions and the topographical plot was plotted in Fig. 4 to Fig. 6. The analysis of the brainwave pattern is done using Python v3.11 and Matlab 2023b, The Math Works Incorporation.

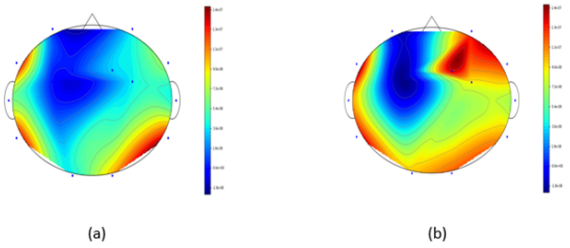

Figure 4: The topographical plot of ADHD subject 2 (a) Pre and (b) Post entrainment sessions.The Δ shows the frontal side of the brain .

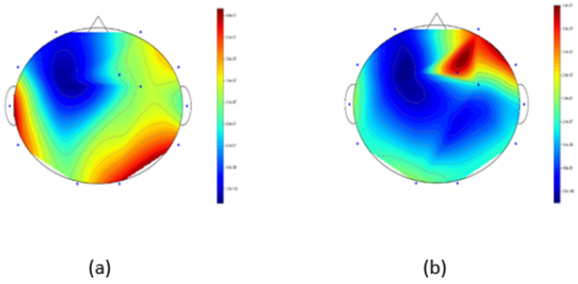

Figure 5: The topographical plot of ASD subject (a) Pre and (b) Post entrainment sessions.The Δ shows the frontal side of the brain.

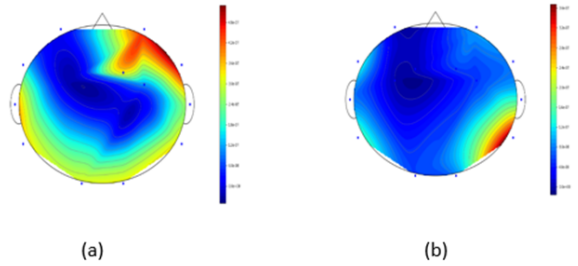

Figure 6: The topographical plot of Comorbid subject (a) Pre and (b) Post entrainment sessions. The Δ shows the frontal side of the brain

The above topographical plot in Fig. 4 shows that the intensity at the frontal region that is responsible for spatial learning is active post AVE sessions. Similar kind of result can be seen in ASD plot in Fig. 5 as well but in Comorbid condition in Fig. 6 the intensity level was reduced post AVE sessions representing the calmness in the brain region. This indicates that the attention and spatial learning in case of subjects with comorbid conditions did not improve as for those subjects with ADHD.

4.1. Quantitative (Comparative) Analysis of Data

Relative band power at Theta, Alpha, and Beta frequency bands was computed using the formulae given in Eq. (2) to Eq. (9) and the comparative analysis is done between pre and post session data. The band power ratios were considered as features that describe the change in the

brain pattern before and after the AVE sessions. The calculated values of Relative Theta (RT), Relative Alpha (RA), Theta to Beta (TBR), Theta to Alpha Beta (TABR) values was expected to reduce after brainwave entrainment sessions and at the same time Relative Beta (RB) and Beta to Theta Alpha ratio (BTAR) values were expected to increase after the entrainment sessions for ADHD, ASD and Comorbid conditions. The values that indicate the change between pre and post session data are given below in Table 3, Table 4 and Table 5. The calculations were done using Python version 3.11. The values in the grey colors indicate that the change was as expected as per the hypothesis of the research while the values in white color represent that the change was not as expected.

Table 3: Change in feature parameters before and after AVE sessions in ADHD subjects

ADHD	RT	RA	RB	TB	TAB	BTA
1	-0.11	0.38	0.07	-0.17	-0.25	0.08
2	-0.02	0.02	0.04	-0.06	0.03	0.05
3	-0.07	-0.02	0.33	-0.30	-0.11	0.41
4	0.24	-0.15	-0.35	0.91	0.75	-0.41
5	-0.03	0.07	-0.05	0.03	-0.03	-0.06
6	-0.03	0.04	0.07	-0.09	0.00	0.08
7	0.05	-0.07	-0.02	0.07	0.23	-0.03
8	0.31	-0.26	-0.47	1.46	1.18	-0.53
9	-0.04	0.01	0.14	-0.16	-0.06	0.16
10	0.01	-0.03	0.01	0.01	0.14	0.01
11	-0.03	-0.20	0.73	-0.44	-0.07	0.90

Table 4: Change in feature parameters before and after AVE sessions in Comorbid (ADHD+ASD) subjects.

Com	RT	RA	RB	TB	TAB	BTA
12	-0.07	0.08	0.24	-0.25	-0.07	0.29
13	-0.08	0.12	0.32	-0.30	-0.17	0.36
14	0.03	0.01	-0.18	0.26	0.18	-0.20
15	0.04	-0.08	-0.17	0.25	0.23	-0.18
16	-0.20	0.16	0.59	-0.50	-0.34	0.75
17	-0.04	0.08	0.02	-0.06	-0.01	0.02

Table 5: Change in feature parameters before and after AVE sessions in ASD subjects

ASD	RT	RA	RB	TB	TAB	BTA
18	0.21	-0.20	-0.46	1.23	0.77	-0.50
19	0.02	0.05	-0.18	0.24	0.09	-0.20
20	0.19	-0.03	-0.35	0.83	0.44	-0.40
21	0.00	-0.01	0.05	-0.05	0.04	0.05
22	0.56	-0.29	-0.61	3.00	1.90	-0.67
23	0.11	-0.24	-0.15	0.32	0.51	-0.17

The above ADHD subject data in Table 3 represents that the relative theta power is suppressed in 8 subjects 1,2,3,4,5,6,9 and 11 and beta power is invoked to a little extent in 7 subjects 1,2,3,6,9,10,11. The Theta to Beta ratio reduced in 6 subjects 1,2,3,6,9,11 out of 11 ADHD subjects which is represented in graphical form in Fig. 7. The pre and post theta to beta ratio data is given in Fig. 10.The ratio of Beta to Theta and Alpha increased in 7 subjects 1,2,3,6,9,10,11. This data represents a positive change in 8 subjects and a negative change in 3 subjects in case of ADHD. Table 4 represents the comorbid subject data in which the relative theta power is suppressed in 4 subjects 12,13,16,17 and relative beta power is invoked in 4 subjects 12,13,16,17. The same is depicted in bar plot in Fig. 8. The pre and post theta to beta ratio data is given in Fig. 11. Table 5 contains the ASD subject data in which relative theta is not reduced and relative beta value is invoked in 1 subject 21 . The graphical representation of the data is given in Fig. 9. The pre and post theta to beta ratio data is given in Fig. 12.

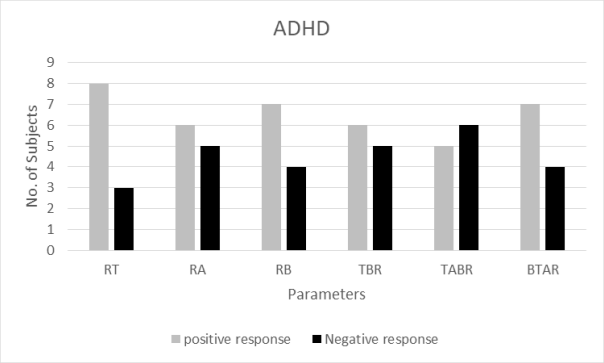

Figure 7: Graphical representation of the number of subjects who responded positively and negatively to the AVE sessions

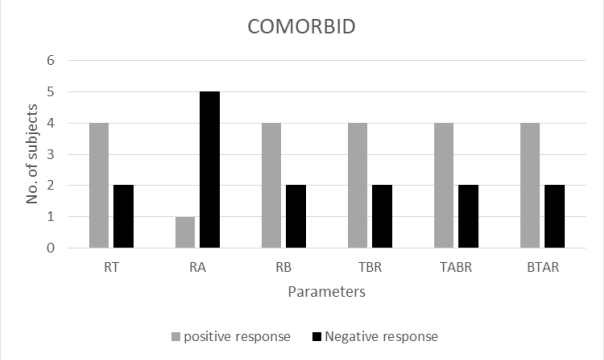

Figure 8: Graphical representation of the number of subjects who responded positively and negatively to the AVE sessions.

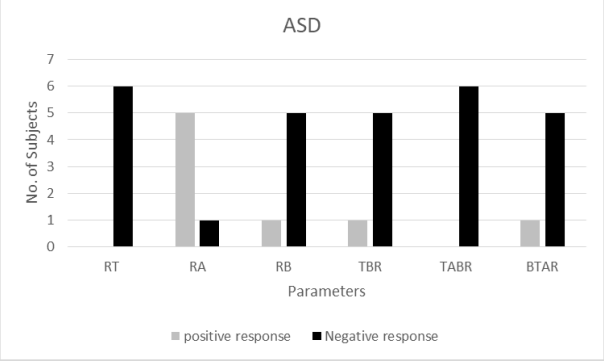

Figure 9: Graphical representation of the number of subjects who responded positively and negatively to the AVE sessions.

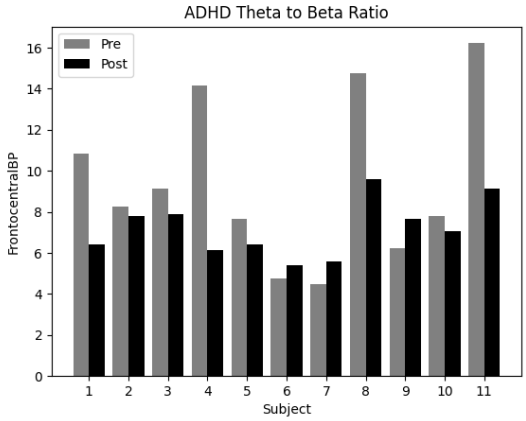

Figure 10: Bar plot of Theta to Beta Ratio before (Pre) and after (Post) the AVE sessions in ADHD subjects.

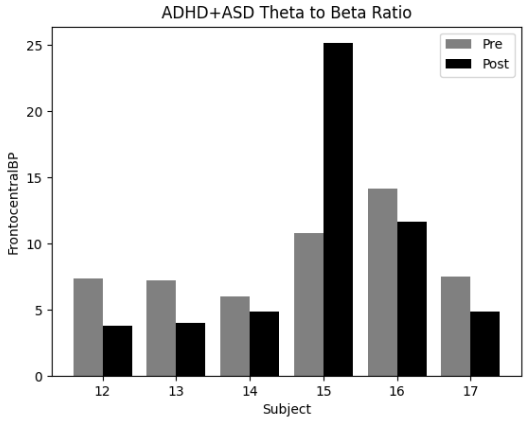

Figure 11: Bar plot of Theta to Beta Ratio before (Pre) and after (Post) the AVE sessions in Comorbidity subjects.

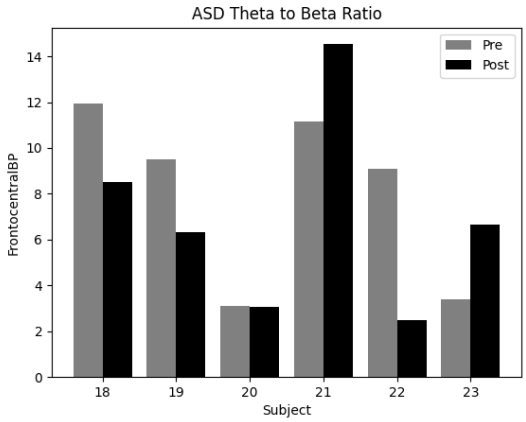

Figure 12: Bar plot of Theta to Beta Ratio before (Pre) and after (Post) the AVE sessions in ASD subjects.

This analysis reveals that 72% of subjects showed a positive change in the case of ADHD, 66% of subjects showed a positive change in the case of Comorbid conditions, and 16% of subjects showed a positive change in the case of ASD.

This experiment does not require a control group in the traditional sense. In the study, we compared individual A's pre-session data with the post-session data of individual A i.e. when the participant is not influenced by AVE and when the participant is influenced by AVE. Thus pre session data is equivalent to the control group.

4.2. Statistical analysis

The outliers in the data were screened using outlier detection algorithm [78]. The test scores were obtained by calculating the standard deviation. The test scores 2.5 times the standard deviation were considered outliers and exempted from further analysis. The box plot shows the outliers in Fig. 13. The results indicate two outliers. One from ADHD subgroup and one from ASD subgroup. The total number of participants for statistical analysis included 21 participants. Participants with good improvement in scores were contacted to check for the possible effects.

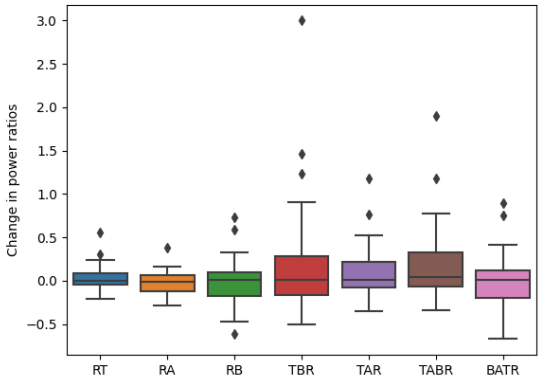

Figure 13: Box plot to detect outliers.

4.2.1. Brainwave Parameters

Since the null correlation is zero, we used the t distribution to test the correlation. The correlation's distribution is not symmetrical when r is not equal to 0, hence we used the Z distribution over Fisher transformation to create the confidence interval. the scatter plots for the parameters are given in Fig. 14 to Fig. 20

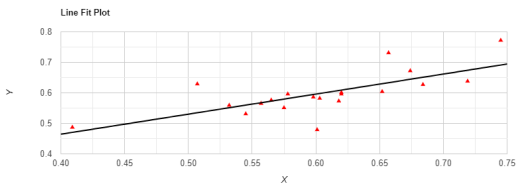

Figure 14: Line fit scatter plot for Relative Theta

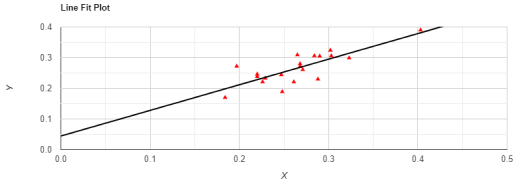

Figure 15: Line fit scatter plot for Relative Alpha

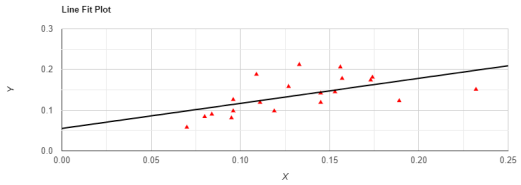

Figure 16: Line fit scatter plot for Relative Beta

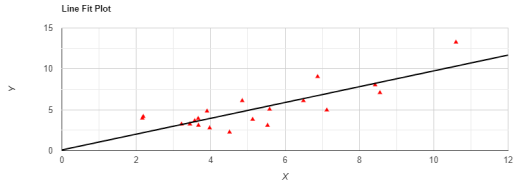

Figure 17: Line fit scatter plot for Theta to Beta ratio

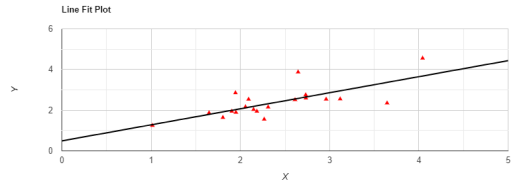

Figure 18: Line fit scatter plot for Theta to Alpha Ratio

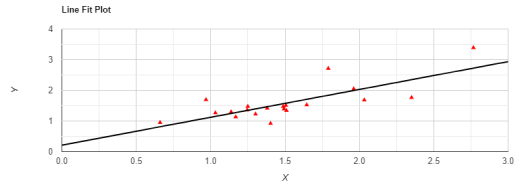

Figure 19: Line fit scatter plot for Theta to Beta and Alpha Ratio

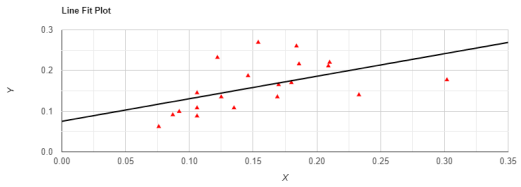

Figure 20: Line fit scatter plot for Beta to Theta and Alpha ratio

The Pearson correlation results in Table 6 indicated that there is a significant positive relationship between X (pre-session data) and Y (post-session data) in Fig. 11 to Fig. 17. The P value state that the difference between the sample correlation and the expected correlation is good enough to be statistically significant.

Table 6: Correlation between Brainwave ratios. * Indicates p less than 0.01

S. No	Parameter (Pre and Post sessions)	Pearson correlation coefficient (r)	Statistic	P-value
1	**RT**	0.7149	4.3381	0.0004*
2	**RA**	0.7971	5.6012	0.00003*
3	**RB**	0.5779	3.0043	0.00762*
4	**TBR**	0.821	6.1005	0.00001*
5	**TAR**	0.7204	4.4073	0.00034*
6	**TABR**	0.7684	5.0942	0.00008*
7	**BTAR**	0.5238	2.6091	0.01775*

5. Results and Discussion

The power spectral density is one of the important factors that indicated the changes that occurred in the brainwave frequency before and after entrainment sessions. The quantitative analysis revealed a positive result in 7 subjects out of 11 subjects based on EEG data which subjects to nearly 72% of the positive result. In the Comorbid category, the feedback from guardians revealed a positive result in 5 subjects out of 6 subjects. In contrast, quantitative analysis revealed that positive results were observed in 4 subjects out of 6 subjects based on EEG data which resulted in positive results in nearly 66% of the subjects. In the case of ASD, the guardian's feedback revealed a positive result in 2 subjects out of 6 subjects whereas the quantitative analysis revealed that positive results were observed in 1 subject out of 6 subjects based on EEG data that subjects to positive results in 16% of subjects. The same is depicted in Fig. 21. The feedback from the guardians of the participants was taken in different forms like messages, emails, word of mouth, etc. An in-depth case study approach and feedback using constructive tools for the clinical participants would have comprehensively elaborated the association of brainwaves with the clinical symptoms of NDs.

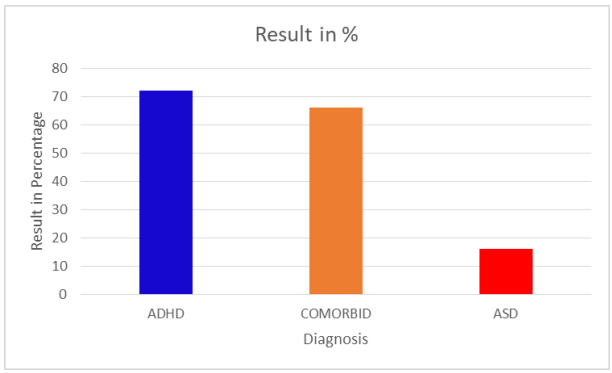

Figure 21: Comparison of effectiveness of AVE of the 3 subgroups.

Overall considerations reveal that 17 out of 23 subjects observed positive results which is 73.9% in the case of behavioral analysis and 12 out of 23 subjects observed positive results which is 52.1% in the case of quantitative analysis. The statistical analysis also shows a positive correlation between pre and post-session data supporting the research. This research also found that there is a reduction in distraction and an improvement in cognitive power which is one

of the most important factors to improve learning but still needs more investigation.

There was a lack of significant improvement in ASD. The reason behind this is the differences in neuroanatomy, functioning, and connectivity within the wider neural systems that probably mediate autistic symptoms and traits. However, the brain development in ASD is complex and is mediated by many genetic and environmental factors and their interactions [79]. Future work can explore the potential strategies to improve the results.

The differences in brainwave band power were analyzed to explore the role of change of theta, alpha, and beta bands post-entrainment sessions. The role of alpha-band oscillations was emphasized as a mechanism for selective attention due to their ability to process potential distracting stimuli [80], recent studies have challenged this theory [81]. Another study highlighted the interactions between theta and alpha/beta responses for visual selective attention among healthy individuals [82]. Further, [83] found the role of the beta frequency band's rhythmic activity in the neuronal correlates of an individual's attentional processes. High theta, low beta ADHD profile is well established in literature [84, 85, 86]. This suggests that an increase in TBR values will result in decreased attention.

Furthermore, in the current study, the individual's theta and alpha PSD affected the alpha activity during the alpha entrainment sessions. Previous studies stated the role of alpha resting state PSD in determining the changes in central alpha asymmetry during alpha and beta entrainment sessions [72]. The current study supports the role of theta and alpha baseline PSD in determining the effects of alpha entrainment. Hence, an individual's baseline frequencies could moderate the entrainment effects leading to individual differences.

Certain limitations need to be considered. The results were based on a small dataset, a larger dataset will give more accurate results. The results may vary when subjects with different dietary and lifestyle habits are considered. The observation time was limited to 20 days, and changes in the long run were unknown. Another limitation is that the scalp EEG is the result of the joint activity from multiple neurons, therefore, separating the source signals when the number of sources is greater than the number of sensors is promising. Another limitation is EEG quality degrades if the subject is not steady. So only the activities that can be done in a sitting position were given during EEG data recording.

6. Conclusion

This research provided evidence not only in the reduction of symptoms of the NDs but also an improvement in attention using audio photic brainwave entrainment. Though several studies show that AVE is a useful tool for treating attentional disorders, the introduction of VR for photic stimulation and portable commercial EEG devices, made it usable out of the lab, within the comfort zone of the subject. Food habits and gut health may also contribute to the improvement in the subject's attention and learning which needs to be considered in further research work. Based on individual psychological health, personalized programmable devices can be developed further. This research also affects the symptoms of Stuttering, Dyslexia, and Neuro developmental delay but needs more investigation. Further research can also explore different approaches or therapies that may be more effective for ASD group.

The study supports the use of technologically assistance to help children with ADHD maintain focus and manage transitions between activities. This can enable educators to personalize instruction and pacing without disrupting overall classroom. The results have important implications for psychosocial interventions for children with neural disorders by emphasizing the need for individualized, developmentally appropriate, and engagement driven approaches. The findings suggest that technology assisted therapies can improve accessibility and scalability of mental health services. The study highlights the shift from traditional, clinical centric models towards more adaptive and patient catered care.Future studies can involve in increasing the data set with diverse participant samples to improve the generalizability of findings across different age groups. Longitudinal study designs would help determine the stability and long-term impact of the observed outcomes.

Acknowledgments

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Consent

The research is approved by the Ethics Committee of DYPIU, Akurdi, Pune, Maharashtra, India. All the participants in the research signed an informed consent form before they participated in the research.

Data Availability

The raw data is the primary data and cannot be provided publicly to protect the privacy and preservation of the anonymity of the participant, but the data and study analysis code are available from the corresponding author on a reasonable request. The band power data are provided in the supplementary information file.

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Dr. Manasa Mandapati has done her bachelor's degree from JNTUH in 2007. She has done her master's degree from NMIMS in 2013. She has completed PGDM in patent law from NALSAR university in 2018. She completed her PhD degree in computer science engineering with specialisation in brain computer interface from DYPIU in 2025.

She has a mixed experience of industry, and academia. She started her career as a project engineer at Wipro technologies from 2008 to 2010. She contributed as a Women Scientist C with TIFAC where she gained exposure to intellectual property rights and innovation driven projects. She also worked as a trainer for IP awareness under NIPAM 2.0. Her area of research is in artificial intelligence, brain computer interface. She is currently working as assistant professor. Published four research papers in reputed journals like Applied Neuropsychology Child.

Prof. Prabhat Ranjan was educated at Netarhat School(near Ranchi), IIT Kharagpur, and Delhi University. He received his Ph.D. from the University of California, Berkeley where he carried out research on "Nuclear Fusion" at Lawrence Berkeley Laboratory from 1983-86.

Prof. Prabhat Ranjan is currently Chairman(Research, Innovation and International Relations) of D Y Patil Pratishthan covering multiple institutions in Pune and Kolhapur. He is also the founder Vice Chancellor of D Y Patil International University(DYPIU), Akurdi, Pune and served in this position from April 2018 to April 2025. From April 2013 to April 2018, he was heading India's Technology Think Tank, TIFAC in Delhi. TIFAC is an autonomous body under the Dept of Science and Technology, Govt of India. Earlier he was Professor at Dhirubhai Ambani Institute for Information and Communication Technology, Gandhinagar (DA-IICT) from 2002 to 2013.