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Neurofeedback Training Aimed to Improve Focused Attention and Alertness in Children With ADHD: A Study of Relative Power of EEG Rhythms Using Custom-Made Software Application

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Abstract

Neurofeedback is a nonpharmacological treatment for attention-deficit hyperactivity disorder (ADHD). We propose that operant conditioning of electroencephalogram (EEG) in neurofeedback training aimed to mitigate inattention and low arousal in ADHD, will be accompanied by changes in EEG bands' relative power. Patients were 18 children diagnosed with ADHD. The neurofeedback protocol ("Focus/Alertness" by Peak Achievement Trainer) has a focused attention and alertness training mode. The neurofeedback protocol provides one for Focus and one for Alertness. This does not allow for collecting information regarding changes in specific EEG bands (delta, theta, alpha, low and high beta, and gamma) power within the 2 to 45 Hz range. Quantitative EEG analysis was completed on each of twelve 25-minute-long sessions using a custom-made MatLab application to determine the relative power of each of the aforementioned EEG bands throughout each session, and from the first session to the last session. Additional statistical analysis determined significant changes in relative power within sessions (from minute 1 to minute 25) and between sessions (from session 1 to session 12). Analysis was of relative power of theta, alpha, low and high beta, theta/alpha, theta/beta, and theta/low beta and theta/high beta ratios. Additional secondary measures of patients' post-neurofeedback outcomes were assessed, using an audiovisual selective attention test (IVA + Plus) and behavioral evaluation scores from the Aberrant Behavior Checklist. Analysis of data computed in the MatLab application, determined that theta/low beta and theta/alpha ratios decreased significantly from session 1 to session 12, and from minute 1 to minute 25 within sessions. The findings regarding EEG changes resulting from brain wave self-regulation training, along with behavioral evaluations, will help elucidate neural mechanisms of neurofeedback aimed to improve focused attention and alertness in ADHD.

Keywords
electroencephalography, neurofeedback, ADHD, selective attention, theta/alpha ratio

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Introduction

Prevalence and Clinical Significance

ADHD is prevalent throughout the world, and approximately 5% of school-aged children have ADHD, with some estimates projecting rates as high as 10%.[1,2] The primary indications of ADHD are moderate-to-extreme inattention, shown by evidenced by the inability to focus attention on specific tasks, and the hyperactivity component, shown by fidgeting, agitation, and impulsivity.[3,4] Most of the children diagnosed with ADHD present frontal executive function deficits[3] and low behavioral self-regulation ability. Almost half of children with ADHD exhibit these symptoms in a chronic manner, which continues into adulthood.[5] Common problems associated with, and attributed to, ADHD include poor academic performance, lower occupational success, increased risk-taking behavior, and diminished social relationships.[5] Literature also cites that ADHD increases the likelihood of other psychiatric diagnoses, which could lead to impaired functional adaptations later in life.[4] Diagnoses of ADHD are commonly associated with psychiatric disorders including, but not limited to, conduct, oppositional defiant and learning disorders.[5-8]

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EEG Characteristics—ADHD and Comorbidities

ADHD has been associated with certain clinical behavioral symptoms for many years. Recently, interest has been focused on ADHD, to determine whether certain abnormal EEG patterns correlate with clinical manifestations of ADHD. Multiple studies[9-11] have determined that compared to gender- and age-matched controls, children with ADHD have greater theta activity.[12,13] Other studies showed an increase in delta activity,[14] coupled with decreased alpha and beta activities.[10,12,14] Additionally, abnormalities in the theta/beta ratio are one of the most significant measures of EEG alterations in ADHD.[13,15,16]

Interest has developed in the connection between EEG patterns and 4 subtypes of ADHD. The 3 *Diagnostic and Statistical Manual of Mental Disorders* (Fourth Edition, *DSM-IV*) subtypes of ADHD investigated were inattentive, hyperactive impulsive, and combined. Inattentive and combined subscales showed a correlation with the theta band. The theta/beta ratio showed a correlation with hyperactive impulsive subtype, as well as with the combined subtype.[8]

Treatment—Nonpharmacological

One non-pharmacological solution, which has yielded positive results, is neurofeedback (also called EEG biofeedback) training. Multiple controlled studies have demonstrated the efficacy of neurofeedback as a treatment for ADHD.[17-19] The primary rationale for the utilization of neurofeedback stems from studies showing abnormal EEG profiles in patients with ADHD[12] In the majority of patients with ADHD, studies have shown that there is cortical slowing or hypoarousal as evidenced by EEG data.[20] Therefore, neurofeedback treatments have been developed to target the 2 previously noted EEG abnormalities. It was theorized that, through reinforcing a specific change in cortical activity using auditory or visual feedback, the patient could normalize this rewarded activity, and develop the ability to maintain and control targeted behavior (e.g. inattention).[20] Neurofeedback is a form of operant conditioning, and self-regulation of EEG is considered as a form of instrumental learning.[18]

Multiple articles have reported neurofeedback as efficacious in ADHD. These include meta-analysis, randomized clinical trials, and literature reviews of neurofeedback.[4,17,18] Furthermore, some reviews consider neurofeedback a Level 5 (efficacious and specific) treatment for ADHD.[18] However, some clinicians have concerns, and argue that neurofeedback should not yet be considered specific and efficacious, and more randomized clinical trials are needed.[21] As indicated by such objections, the efficacy of neurofeedback in ADHD is still far from consensus, and encourages basic EEG research and clinical trials.[22] The current study represents one of the approaches to understanding neurophysiological correlates of neurofeedback.

Several protocols, prevalent in the literature, have shown efficacy in ADHD.[23-26] Most use suppression of theta at frontocentral or central sites, enhancement of low beta (13-18 Hz), or enhancement of sensory motor rhythm (SMR, 12-15 Hz) at the central sites (C3, Cz, C4). One more approach (so-called Focus/Alertness training) uses wide band EEG spectrum regulation training[27,28] at the prefrontal site rather than control of individual bands at frontocentral and central topographies. The Focus/Alertness training protocol is based on the BioExplorer (CyberEvolution, Seattle, Washington) software platform for the Peak Achievement Trainer (PAT) device from NeuroTek LLC (Goshen, Kentucky).[28] According to the PAT manufacturer[28] the Focus training measure is related to focused attention. In the PAT manual,[28] this protocol is also referred to as InhibitAll, or wide band EEG amplitude inhibition control, whereas Alertness is an EEG measure derived using real-time spectral analysis reflecting arousal of the central nervous system. The precise formulas for Focus and Alertness measures calculation are not disclosed, as they are claimed as trade secrets.[28] A prior pilot study, conducted in our laboratory, has shown positive outcomes, using this device (PAT, NeuroTek, Kentucky) and the Focus/Alertness training protocol.[27]

Goals and Expectations

The goal of this study was to conduct neurofeedback in participants with ADHD, using the PAT device with the Focus/Alertness training protocol to investigate:

1. relative changes in EEG bands of interest throughout the entire course of neurofeedback using custom-made Matlab application,
2. whether success of neurofeedback over 12 sessions could be shown through neurocognitive and behavioral evaluation measures, and most important, how EEG power ratios change during individual sessions and between sessions within the course of neurofeedback.

It was expected that all participants would complete 12 sessions of Focus/Alertness training and learn to increase Focus, and control Alertness. Additionally, it was expected that there would be an improvement in the behavioral questionnaire[29] and neurocognitive test[30] as previously reported in the treatment of ADHD with neurofeedback.[27] It was anticipated that an increase in the Focus measure would result in the gradual decrease of theta/beta and theta/alpha EEG ratios.

Methods

Patient Demographics and Recruitment

Eighteen children and adolescents with ADHD (mean age 13.6 years, standard deviation [SD] = 3.5, 6 females, 12 males) were enrolled. Only 4 participants were not taking stimulant medication. Participants were not required to be off medication during neurofeedback. However, all participants were requested not to take medication before the neurofeedback session. Participants with ADHD were recruited through the University of Louisville Weisskopf Child Evaluation Center (WCEC). Diagnosis of ADHD was based on *DSM-IV-TR*[1] criteria (ADHD/inattentive/

hyperactive/impulsive, and combined type), using a structured parent interview (*Diagnostic Interview for Children and Adolescents-IV* [*DICA-IV*])[31], and was determined by a clinical psychologist and a child and adolescent psychiatrist. *DSM-IV* requires that symptoms be present in at least 2 settings; therefore, prior to the interview, 2 rating scales were administered to parent and teacher (parent—Achenbach Parent Form[32] and The Conners Parent Rating Scale-R[33]; teacher—Achenbach Teacher Rating Form and Conners Teacher Rating Scale-R[32,33]). Participants met criteria for ADHD on at least 1 of 2 parent and on 1 of 2 teacher rating scales; the child also met criteria on the *DICA-IV*. In addition to diagnosis, the psychiatrist and psychologist performed pre- and post-neurofeedback clinical evaluations. Neurofeedback sessions were conducted by an experienced electrophysiologist with extensive background in biofeedback training. All required institutional review board–approved consent/assent forms were signed by the participants and their parent/guardian.

Neurofeedback Protocol and Data Collection

The goal was to enhance Focus throughout the session while maintaining an adequate level of Alertness within a certain range. All sessions were completed using different fragments of documentary films depicting nature scenes from the BBC's "Planet Earth" and "Life" series. Different scenes were utilized to maintain engagement. Based on the thresholds set, the participant would receive biofeedback in visual and auditory modalities. Visual feedback was arranged in a form of control of brightness, size, and continuation of the video by the Focus and Alertness measures. Auditory feedback was used to inform participants when these measures were under the threshold level, in the case of Focus, or outside the acceptable range, in the case of Alertness. All EEG signals and training parameters were measured using 3 electrodes, one active electrode at the prefrontal EEG (FPz) site, the second being a reference on the left ear, and a third as a ground at the right earlobe. The sensors were soaked in a potassium chloride solution to enhance conduction.

Each participant completed a minimum of 12 weekly sessions. The target length of each session was 25 minutes, with most sessions (85%) reaching the goal of a 20-minute minimum recording of EEG data ($n = 185$ sessions out of 216 total sessions). Eye blink artifact removal was implemented using a custom-made BioExplorer (BioExplorer 1.5, CyberEvolution, Washington) application.

Behavioral Measures and Evaluation

Two parents' behavioral ratings, along with pre- and post-neurofeedback data, were collected. Behavioral outcome measures included scores from the Aberrant Behavior Checklist (ABC).[29] The ABC is a rating scale assessing 5 problem areas based on caregiver reports: irritability, lethargy/social withdrawal, stereotypy, hyperactivity, and inappropriate speech.[29] Of particular interest were hyperactivity, lethargy, and irritability.

In addition, as a secondary outcome, neuropsychological measures of selective attention were collected. The continuous performance selective attention test IVA+Plus (BrainTrain Inc, Virginia)[30] was administered before and after the 12-session long neurofeedback course. This 20-minute-long computerized audiovisual selective attention test provides measures of sustained auditory and visual attention quotients, reaction times and other attention scores. It is considered an acceptable neurocognitive test for attention evaluation in children.

The EEG Signal Processing

MatLab (MathWorks, Inc, Massachusetts) was used to code an application that could effectively analyze and compute all the desired measures. Initially, the EEG signal was collected and recorded with a BioExplorer-based software application. The first goal of signal processing was to separate the raw signal based on the desired frequency bands. The first step in the filtering process was completed in BioReview—an extension of BioExplorer that serves for analysis of recorded sessions. The frequency ranges for each selected band are similar, with a slight modification, to those described by Miller in 2007.[34] The signal was separated into delta (2-4 Hz), theta (4-8 Hz), alpha (8-13 Hz), low beta (13-18 Hz), high beta (18-30 Hz), and gamma (30-45 Hz) bands. The raw signal was band-pass filtered in MatLab from 2 to 45 Hz, using a custom band-pass filter application created through the integration of wavelet transformation of the raw signal, and a Harris window configuration that separates the 2 to 45 Hz portion of the raw signal into its own filtered signal. The continuous wavelet transformation of the signal is shown in Equation 1, where S (scale) = 1/ frequency; Tau (τ) = time shift; Psi (ψ) = mother wavelet (in our case the Morlet window).

$$\mathrm{CWT}\frac{\psi}{x}(\tau, s) = \frac{1}{\sqrt{s}}\int\left[(x(t)\psi\ )\ \left(\frac{t-\tau}{s}\right)dt\right]$$

A Morlet Window was used to separate the raw signal into 128 coefficients. The coefficients were then filtered to the desired frequency, using the Harris window configuration. Finally, the filtered coefficients were summed to produce a reconstructed filtered signal. Figure 1 provides a representation of the wavelet transformation and filtering processes. Band-pass filtering of the raw signal in MatLab provided a total signal (2-45 Hz) that could then be utilized in relative power calculations. In contrast to conventional band-pass filtering, integration of the wavelet transformation does not allow for a shift in the time domain while filtering the signal.

Relative power calculations for each minute of every neurofeedback session were completed in MatLab, using an iterative "for loop" function on each recorded session, with the total signal replacing the raw signal. In addition to the calculation of relative power for each band, the ratio of certain bands was calculated. The formula used to calculate relative power is given in equation (2), where *b* represents the band signal and

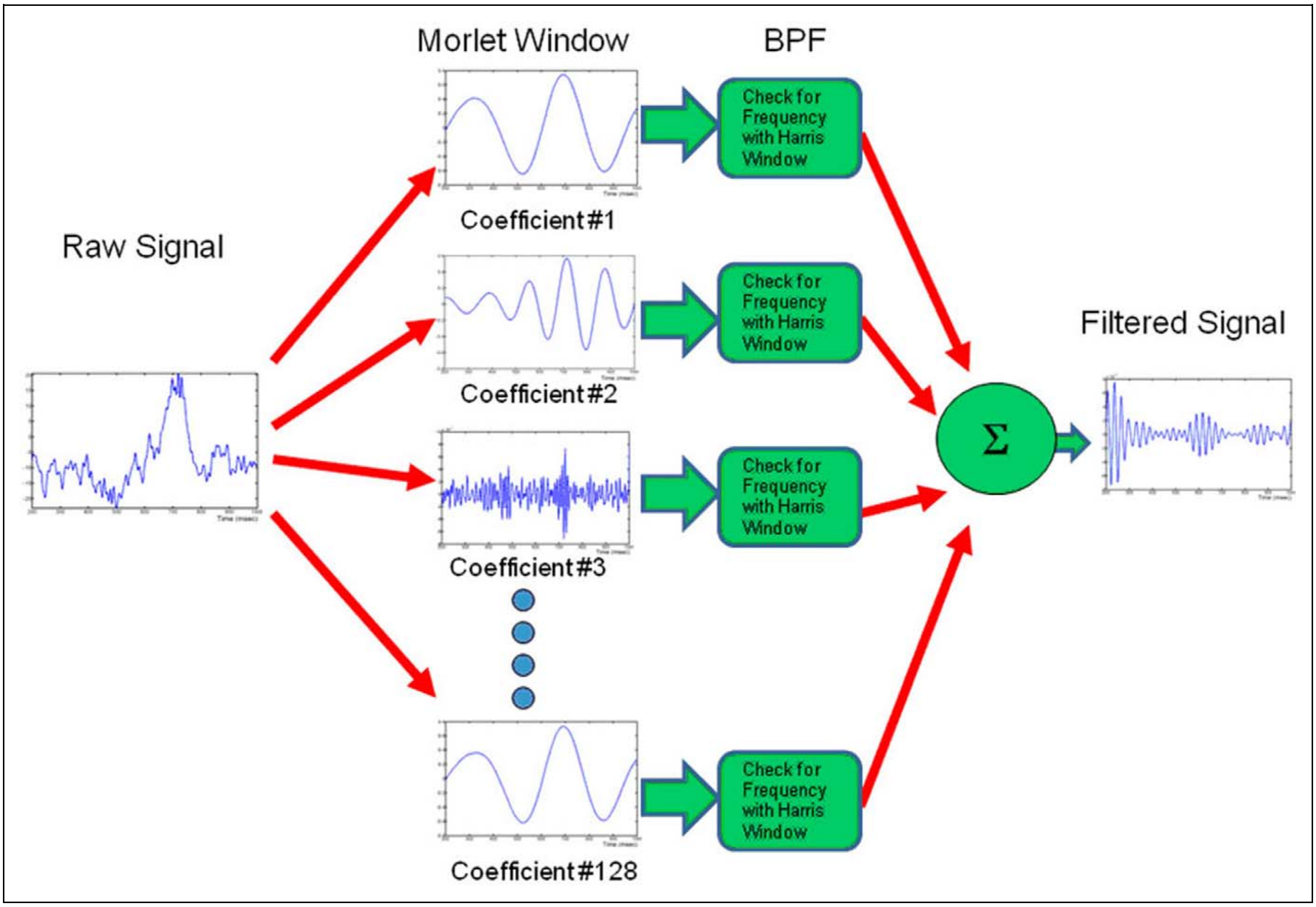

Figure 1. A schematic representation of the wavelet transformation and band-pass filtering applications utilized to filter the raw signal into the desired filtered signal to be used for relative power calculations.

t represents the total signal from 2 to 45 Hz.

$$\sum_{0}^{i} b^2 \bigg/ \sum_{0}^{i} t^2$$

The ratios of interest for this study were theta/low beta, theta/high beta, theta/beta, and theta/alpha proportions. Theta/beta ratio was calculated using the sum of the low beta and high beta relative powers for each minute of each session.

Statistical Analysis

Statistical analysis determined the significance of session number (1-12) and minute (1-25), with regard to each EEG measure calculated. A repeated measures analysis of variance (ANOVA) was utilized with $\alpha = .05$ to determine significant changes in each EEG band and EEG band ratios. Additionally, Student 2-tailed t test was used to determine significant changes between pre- and post-data collected through the IVA + Plus test[30] and the ABC survey.[29] Statistical analysis was conducted using MiniTab 16.0 (State College, Pennsylvania) and SPSS v 15 (SPSS, Inc, Illinois).

Results

The EEG Measure Changes by Session Within the Course of Neurofeedback

ANOVA showed main effects of session for all chosen EEG measures. Specifically, the effect was significant for theta relative power ($F_{11,\ 264} = 6.96$, $P < .001$), low beta relative power ($F_{11,\ 264} = 6.85$, $P < .001$), theta/low beta ratio ($F_{11,\ 264} = 9.02$, $P < .001$), and theta/alpha ratio ($F_{11,\ 264} = 19.74$, $P < .0010$). ANOVA results for EEG measures from session 1 to session 12 are shown in Table 1.

Changes were determined to be either increasing or decreasing based on the trend the data exhibited when charted. Therefore, from session 1 to 12 theta relative power, theta/low beta ratio, and theta/alpha ratios were significantly decreasing. An increase was seen for low beta relative power. Changes in theta/low beta ratio and theta/alpha ratio measures were of particular interest. To gain an understanding of the relationship between changes in session number and these measures, the average value for each session of each EEG measure was plotted from session 1 to 12. Figures 2 and 3 display the change in average theta/low beta ratio and theta/alpha ratio, respectively, across 12 sessions. A linear

Table 1. Summary of ANOVA Results for Changes in EEG Measures from Session 1 to 12 of NFB.[a]

EEG Measure	Degrees of Freedom	*F* Statistic	*P* Value	Direction of Change
Delta relative power	11	8.03	< .001	Decrease
Theta relative power	11	6.96	< .001	Decrease
Alpha relative power	11	7.74	< .001	Increase
Low beta relative power	11	6.85	< .001	Increase
High beta relative power	11	5.67	< .001	Decrease
Gamma relative power	11	5.97	< .001	Decrease
Theta / low beta ratio	11	9.02	< .001	Decrease
Theta / high beta ratio	11	7.64	< .001	Decrease
Theta / beta ratio	11	7.49	< .001	Decrease
Theta / alpha ratio	11	19.74	< .001	Decrease

Abbreviations: NFB, neurofeedback; ANOVA, analysis of variance.
[a] A *P* value <.05 was considered significant for the ANOVA.

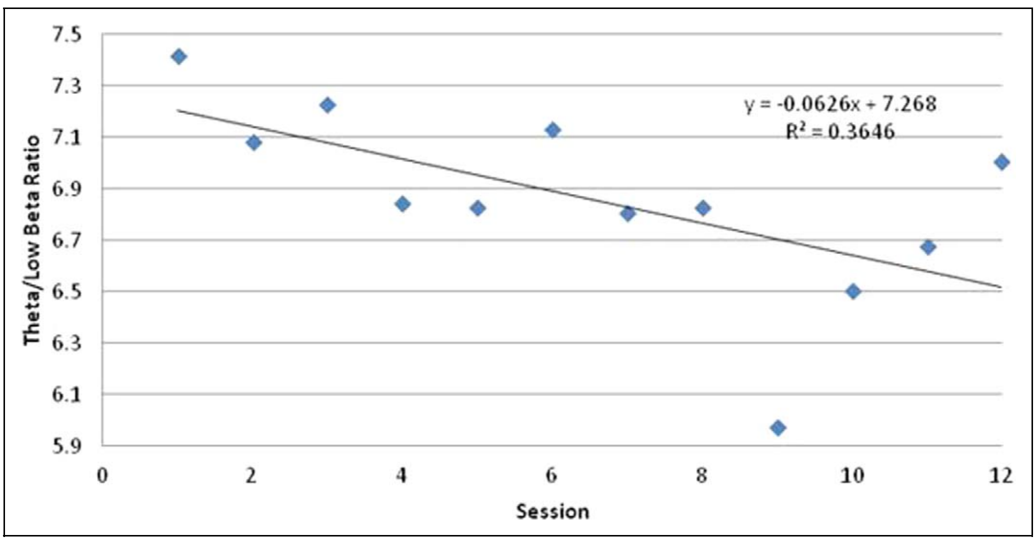

Figure 2. Plot of average theta/low beta ratio value for each session (session number 1-12) indicating a decrease in the value of theta/low beta ratio as the session number increases. R^2 value and equation for linear relationship included on the plot.

relationship is the most obvious fit for average changes from session 1 to 12.

The EEG Measure Changes by Minute Within Individual Session

ANOVA showed that there were main effects of minutes in a session for some EEG measures. The effect of time within a session was determined to be significant for theta relative power ($F_{24,\ 264} = 0.98$, $P = .493$) or low beta relative power ($F_{24,\ 264} = 0.88$, $P = .633$). However, the theta/low beta ratio ($F_{24,\ 264} = 2.12$, $P = .002$), theta/alpha ratio ($F_{24,\ 264} = 2.05$, $P = .003$), and Focus measure ($F_{24,\ 264} = 4.35$, $P < .001$) changed significantly according to duration within a session. ANOVA results are shown in Table 2.

From minute 1 to 25 within a session, theta/low beta ratio and theta/alpha ratios significantly decreased. As with the changes across sessions, changes in theta/low beta ratio and theta/alpha ratio across minute of session were of particular interest. To show changes in theta/low beta ratio and theta/alpha ratio measures depending on minute of a neurofeedback session, the average value for each minute of each EEG measure was plotted. Figures 4 and 5 outline the changes in average theta/low beta ratio and theta/alpha ratio, respectively, from minute 1 to 25. With regard to changes within a session, a logarithmic was a better fit than a linear relationship.

The IVA+Plus and ABC Survey—Pre- and Post-neurofeedback

Student *t* test performed on the IVA + Plus test yielded multiple measures showing a significant change from pre- to post-neurofeedback. The attention quotient showed a significant change from pre- (78.00 ± 6.33) to post-neurofeedback (87.22 ± 5.68); $t(17) = -2.576$, $P = .02$. The attention quotient—visual showed a significant change from pre- (89.89 ± 4.40) to post-neurofeedback (97.89 ± 3.315); $t(17) = -2.285$, $P = .035$. The sustained visual attention quotient showed a significant change from pre- (83.44 ± 5.64) to post-neurofeedback

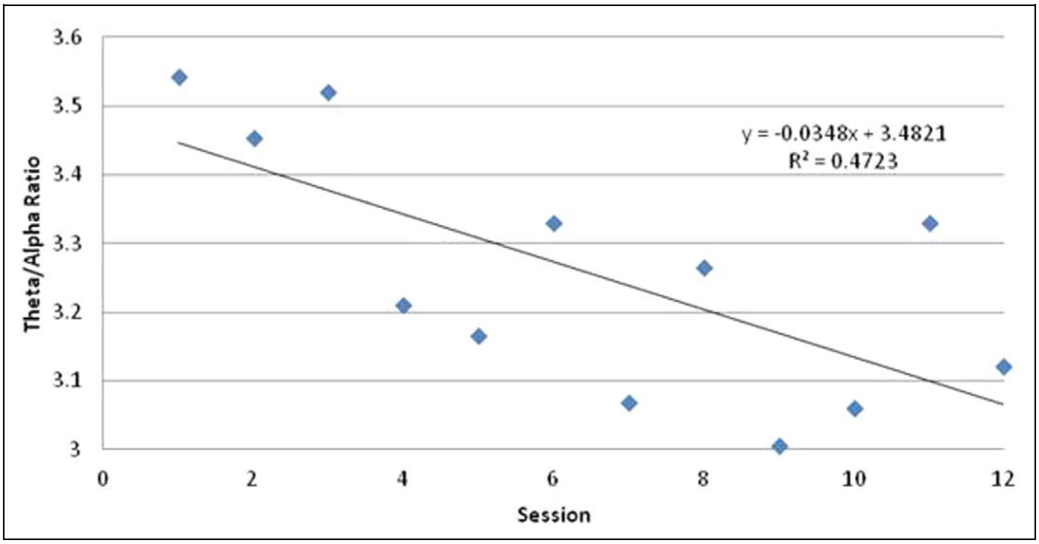

Figure 3. Plot of average theta/alpha ratio value for each session (session number 1-12) indicating a decrease in the value of theta/alpha ratio as the session number increases. R^2 value and equation for linear relationship included on the plot.

Table 2. Summary of ANOVA results for changes in EEG measures from minute 1 to 25 of NFB Within a Session.[a]

EEG Measure	Degrees of freedom	*F* statistic	*P* value	Direction of change
Delta relative power	24	1.64	.032	Decrease
Theta relative power	24	0.98	.493	NS
Alpha relative power	24	0.71	.841	NS
Low beta relative power	24	0.88	.633	NS
High beta relative power	24	1.58	.045	Increase
Gamma relative power	24	1.66	.029	Increase
Theta / low beta ratio	24	2.12	.002	Decrease
Theta / high beta ratio	24	6.11	< .001	Decrease
Theta / beta ratio	24	4.82	< .001	Decrease
Theta / alpha ratio	24	2.05	.003	Decrease

Abbreviations: NFB, neurofeedback; ANOVA, analysis of variance.
[a] A *P* value <.05 was considered significant for the ANOVA.

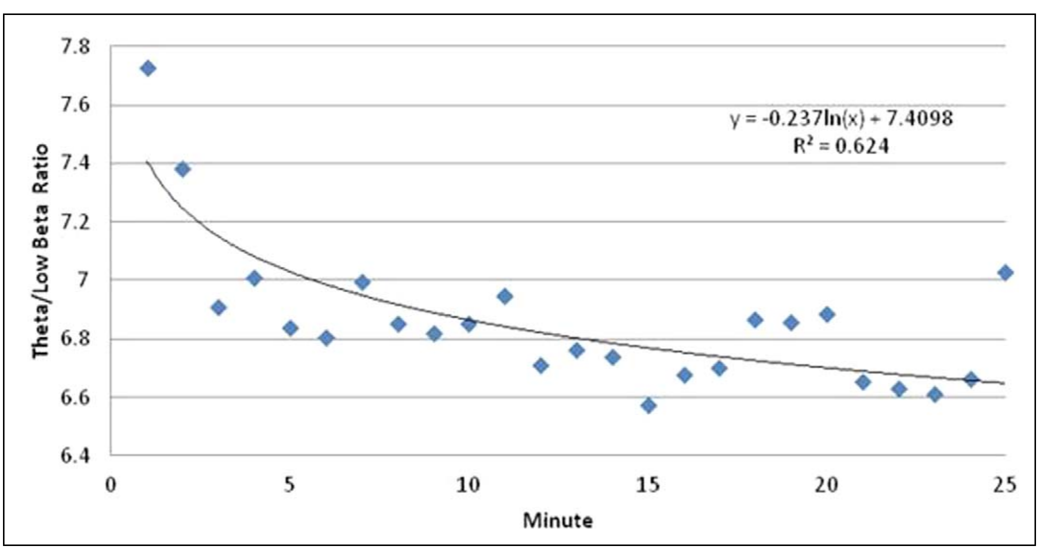

Figure 4. Plot of average theta/low beta ratios (averaged across all sessions) for each minute of neurofeedback ([NFB] 1-25) indicating a decreasing theta/low beta ratio as minute of NFB within a session increases. R^2 value and equation for logarithmic relationship included on the plot.

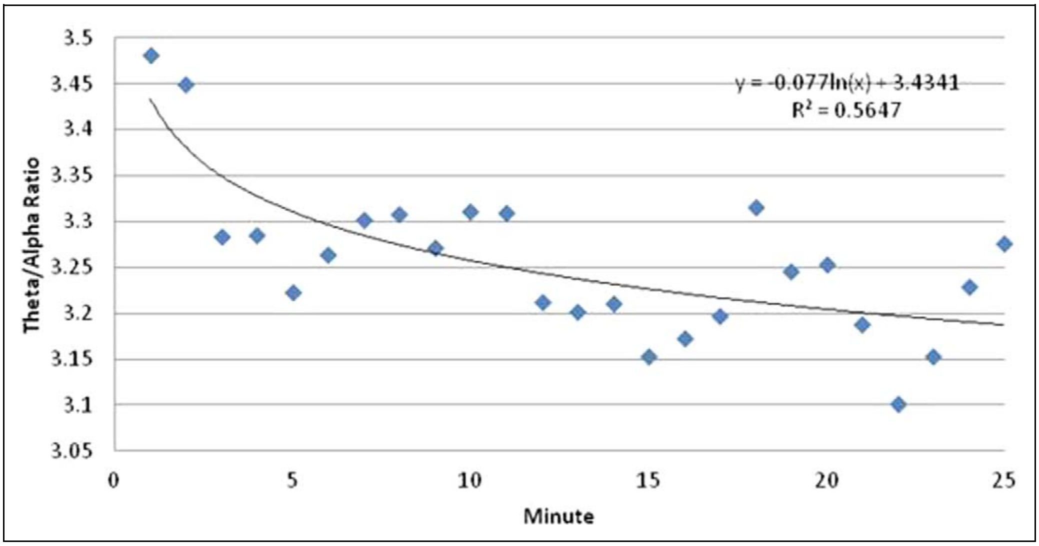

Figure 5. Plot of average theta/alpha ratios (averaged across all sessions) for each minute of neurofeedback ([NFB] 1-25) indicating a decreasing theta/alpha ratio as minute of NFB within a session increases. R^2 value and equation for logarithmic relationship included on the plot.

Table 3. Summary of Significant Changes Within the IVA+Plus Test From Comparing Data From Pre- and Post-Neurofeedback.[a]

Measure	Pre-NFB mean ± SE	Post-NFB mean ± SE	*t* Statistic	*P* value	Change from pre- NFB to post-NFB
Attention quotient	78.00 ± 6.33	87.22 ± 5.68	2.57	.020	Increase
Attention quotient auditory	70.89 ± 7.62	79.06 ± 7.94	2.01	.060	NS
Attention quotient visual	89.89 ± 4.40	97.89 ± 3.315	2.28	.035	Increase
Response control quotient	87.83 ± 4.07	90.33 ± 4.69	0.42	.677	NS
Response control quotient auditory	87.50 ± 4.60	93.28 ± 3.74	1.06	.301	Increase
Response control quotient visual	91.39 ± 3.57	89.94 ± 4.94	−0.25	.803	NS
Sustained auditory attention quotient	60.83 ± 9.44	74.11 ± 9.41	2.00	.061	NS
Sustained visual attention quotient	83.44 ± 5.64	97.83 ± 4.92	2.72	.015	Increase
Auditory reaction time (ms)	735.56 ± 30.54	699.00 ± 31.98	−1.81	.088	NS
Visual reaction time (ms)	490.78 ± 22.87	468.94 ± 19.45	−2.37	.029	Decrease

Abbreviations: NFB, neurofeedback; SE, standard error; NS, not significant.
[a] A *P* value <.05 was Considered Significant for the 2-tailed *t* test.

Table 4. Summary of Significant Changes in Clinical Measures as Indicated by the Aberrant Behavior Checklist Survey Using a 2-Tailed *t* Test Comparing Data of Pre- and Post-Neurofeedback.[a]

Measure	Pre-NFB mean ± SE	Post-NFB Mean ± SE	*t* Statistic	*P* value	Change from pre-NFB to post-NFB
Irritability	11.67 ± 2.16	8.33 ± 2.01	3.602	.002	Decrease
Lethargy	8.00 ± 2.04	3.94 ± 1.25	2.366	.030	Decrease
Stereotypy	3.89 ± 1.37	2.56 ± 1.01	2.515	.022	Decrease
Hyperactivity	15.28 ± 3.24	10.83 ± 2.44	3.189	.005	Decrease
Inappropriate speech	2.94 ± 0.75	1.94 ± 0.64	4.675	< .001	Decrease

Abbreviations: NFB, neurofeedback; SE, standard error.
[a] A *P* value <.05 was considered significant for the *t* test.

(97.83 ± 4.92); $t(17) = -2.721$, $P = .015$. The visual reaction time (ms) showed a significant change from pre- (490.78 ± 22.87 ms) to post-neurofeedback (468.94 ± 19.45 ms); $t(17) = 2.379$, $P = .029$. Table 3 shows the IVA + Plus *t* test results on 10 various measures.

The ABC survey showed significant changes from pre- to post-neurofeedback. Specifically, hyperactivity showed a significant change from pre- (15.28 ± 3.24) to post-neurofeedback (10.83 ± 2.44); $t(17) = 3.189$, $P = .005$. Table 4 summarizes the results of the *t* test for the ABC outcomes.

Discussion

Results in Tables 1 and 2 indicate outcomes which are primarily expected in relative power of chosen bands and change in ratios. For instance, the theta band is shown to decrease across

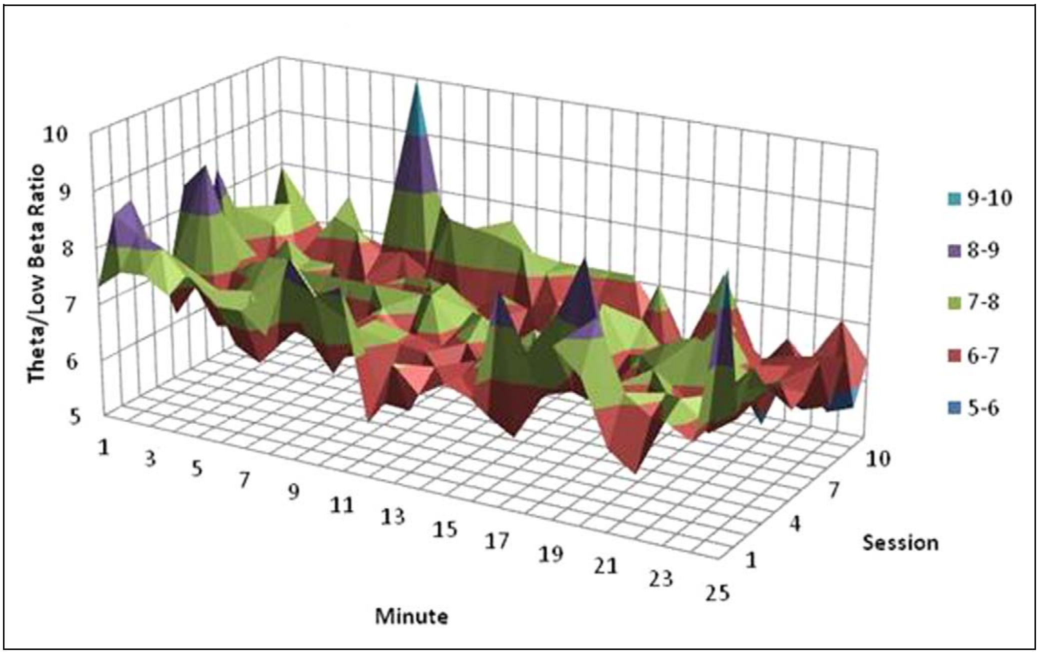

Figure 6. The surface chart provides evidence supporting the decrease in the theta/low beta ratio with regard to increasing session number and increasing minute of each session. As is consistent with the results of the analysis of variance (ANOVA), session trends, and minute trend analysis, a general decrease is seen from (session 1, minute 1) through (session 12, minute 25) for the theta/low beta ratio. The legend on the right side of the figure gives the color-coded ranges for the theta/low beta ratio, as seen in the chart.

sessions and minutes within a session, while the alpha band is shown to increase for both criteria. Therefore, the theta/alpha band should decrease for both session and minute within a session. This is shown in Figures 2 and 4. However, several bands (high beta and gamma) show counterintuitive results at first glance. Upon further inspection of the protocol and the changes within each band, this discrepancy can be rationalized and explained. The high beta band increases in relative power within session, but decreases from session to session. However, the session-to-session changes show very low correlation. The increase within session in the gamma range could be the result of an increase in a subjective sense of achievement attained through mastery of the assigned skill (i.e., increasing ability to focus attention). It has been suggested that an increase in prefrontal gamma activity could be tied to emotional responses and the effort associated with learning.[35] Therefore, the decrease in gamma from session to session could be the result of the participant having a lower effort to master this skill of concentration of attention.

As shown in Tables 2 to 5 and Figures 2 to 5, the most notable indications of this analysis are a decrease in theta/low beta and theta/alpha proportions from session to session and from 1 to 25 minutes within a session. Results show consistency with the overall aims and goals of neurofeedback.[20] Specifically, this claim can be made regarding the decrease in the theta/low beta ratio. A net reduction in theta/low beta ratio was seen across both sessions and minute within a session. These findings support the treatment of EEG irregularities within the population with ADHD [12] with neurofeedback. Figures 6 and 7 provide illustration of the observed changes, as a result of session number and minute within session, through a surface chart representing a 3-dimensional view of the data.

In this study, theta was the EEG between 4 and 8 Hz, whereas alpha was between 8 and 13 Hz. A reduction in the theta/alpha proportion was seen across both sessions and minute within a session. As with the evidence for changing theta/low beta ratio values (Figure 6), visual illustration of a decrease in theta/alpha ratio as a function of session number and minute within a session is provided in Figure 7.

Participants with ADHD, especially the inattentive subtype, have similar EEG characteristics.[8] This is evident in the theta/beta proportion being similar in the first session to that encountered in other studies of ADHD.[13,15,16] In this analysis, the average session one value for the theta/low beta proportion was 7.4, which is similar to the baseline value of 6.4 to 6.6 reported by Monastra for theta/beta values for similar frequencies[36] and current data of Ogrim et al[15] (7.02-7.08 for young ADHD, and 6.21 for adult ADHD)

Improvements in behavior, indicated by IVA + Plus. ABC, require discussion to determine whether training of the Focus/Alertness measures, or the theta/beta and theta/alpha ratio changes, are more important to functional improvement. Determination of the measure more fundamental to treatment of ADHD would increase the efficacy of neurofeedback treatment methods.

Similar to prior work, this study indicates neurofeedback for altering EEG characteristics associated with the disorder.[4,5,17,18,20,22,27] The positive effects of neurofeedback corresponded to improvement in the behavioral measures and functional outcomes seen in the IVA+Plus test and the ABC survey.

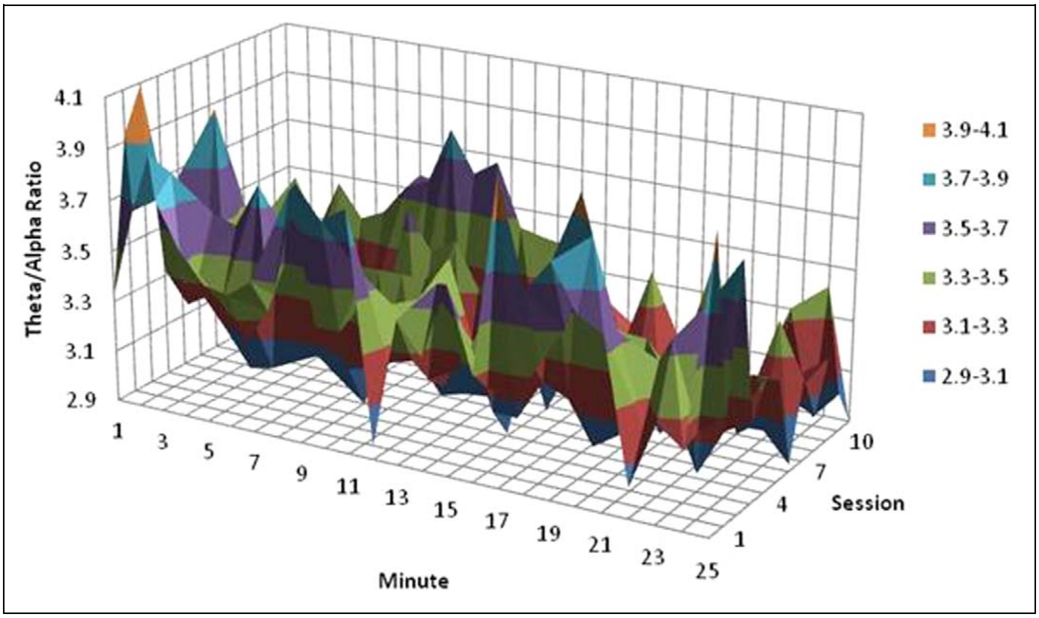

Figure 7. The surface chart provides evidence supporting the decrease in the theta/alpha ratio with regard to increasing session number and increasing minute of each session. As is consistent with the results of the analysis of variance (ANOVA), session trends, and minute trend analysis, a general decrease is seen from (session 1, minute 1) through (session 12, minute 25) for the theta/alpha ratio. The legend on the right side of the figure gives the color-coded ranges for the theta/alpha ratio, as seen in the chart.

Absence of the post-neurofeedback parent and teacher ratings, as in Achenbach[32] and Conners[33] should be mentioned as a limitation of this pilot study. Since this exploratory study did not use a controlled design, we are not claiming clinical efficacy but rather consider it as an investigation of EEG bands relative powers and their ratios across 12 sessions of neurofeedback aimed to enhance focused attention. This is a methodological study that uses quantitative EEG analysis in ADHD children enrolled in neurofeedback treatment, using a specialist device and software, and custom-made MatLab analysis tools.

However, this analysis differs from prior studies in the consideration of what is transpiring not only from session to session, but also within each session. Our study shows that improvement can be indicated within a shorter number of sessions (i.e., 12) compared to previous protocols that required more sessions per participants (>30) to statistically indicate significant improvement either in EEG or in behavioral measures.[4] Probably more than 12 sessions might contribute to better consolidation of results and currently we have a study in progress that will compare outcomes of 12, 18 and 24 sessions of neurofeedback using the same protocol.

Declaration of Conflicting Interests

The authors declared no conflicts of interest with respect to the research, authorship, and/or publication of this article.

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