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Alpha/Theta Neurofeedback Rehabilitation for Improving Attention and Working Memory in Female Students with Learning Disabilities

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Abstract

Learning disabilities (LDs) encompass a range of cognitive challenges that can significantly influence students' educational experiences and overall academic performance. This study aimed to investigate the effects of alpha/theta neurofeedback rehabilitation on attention and working memory in female students with learning disabilities. This study employed a quasi-experimental design with pre-tests, post-tests, and a two-month follow-up and included a control group. Convenience sampling was used to select 40 female students with learning disabilities referred to psychological clinics in Tehran during the 2020-2021 academic year. The participants were randomly assigned to the neurofeedback experimental group (n = 20) or the control group (n = 20). Three students from each group withdrew from the study, leaving 17 participants for the final analysis. Attention and working memory were assessed using the n-back task, Stroop test, and Reverse Stroop test. Data analysis involved mixed repeated ANOVA, independent t-tests, and chi-square tests. The findings revealed that alpha/theta neurofeedback rehabilitation improved all aspects of working memory and attention in female students with learning disabilities during the specified period. These improvements remained consistent during the two-month follow-up ($p < 0.001$). This study demonstrated that alpha/theta neurofeedback rehabilitation can potentially enhance the attention and working memory of female students with learning disabilities.

Keywords
Attention; learning disabilities; memory; neurofeedback; female

1. Introduction

Learning disorders (LDs) are recognized as neurodevelopmental conditions that typically emerge during formal education, characterized by enduring and inhibiting challenges in acquiring fundamental academic abilities such as reading, writing, and mathematics [1]. Diagnosis of LDs is established when there are discernible deficits in an individual's capacity to efficiently and accurately perceive or process information. Crucially, these impairments significantly impede the mastery of specific academic skills, and they cannot be attributed to sensory or motor impairments, intellectual disability, insufficient cognitive abilities, inadequate pedagogical approaches, lack of environmental stimulation, or other external factors [2]. The prevalence of LDs in the general population varies, with estimates ranging from 5% to 15% [2]. However, the observed trends in the prevalence of LDs depend on the studied population and the methodologies used for identification. These conditions include dyslexia, dyscalculia, and others, and the prevalence typically falls between 5% and 9% [3]. This phenomenon is distinguished by heightened theta power in frontal brain regions and diminished alpha power in posterior regions, specifically the parietal and occipital areas. The delayed cerebral development evident in students with LDs has given rise to the hypothesis that LDs may be characterized as a developmental disorder featuring a delay in maturation, consequently hindering their capacity to keep pace with their peers in educational settings[4]. Students with LDs exhibit slower overall brain activity, marked by increased delta and theta power and a corresponding decrease in gamma power in posterior cerebral sites [5]. This characteristic cerebral activity pattern signifies suboptimal management of neural resources, potentially resulting in compromised cognitive performance [6]. Students with LDs often exhibit various cognitive impairments, including difficulties in phonological awareness, attention, and working memory [7].

Working memory (WM) deficits are considered critical contributing factors to LDs. Although different types of LDs in students may be related to other cognitive impairments, working memory deficits are generally involved [8]. A substantial body of research has consistently highlighted working memory capacity as the most commonly compromised cognitive function in students with LDs. Working memory, a pivotal cognitive mechanism, temporarily retains and manipulates information during various mental tasks [9]. Working memory is more influential in students' academic performance than short-term memory. Many academic tasks require multiple steps with intermediate solutions that students must remember as they proceed [10]. Empirical evidence underscores the efficacy of working memory performance as a dependable means of distinguishing between students with LDs and those characterized as slow learners [11]. Within the classroom setting, a working memory deficiency places individuals with LDs at a notable disadvantage. These working memory deficits observed in individuals facing learning challenges arise from inherent neurobiological constraints associated with working memory function and the suboptimal utilization of working memory resources [12].

Individuals with Learning Disabilities (LDs) frequently experience concurrent attentional challenges, which can intensify their condition. Evidence suggests that children with LDs commonly experience attention deficits [13], and studies have shown that students with LDs exhibit attention problems [14]. For instance, students with LDs may struggle to concentrate on texts while inhibiting distracting stimuli [15]. Attention is necessary for perceiving sensory information [16] and maintaining a goal-directed response during continuous and repetitive activities, which can be improved through brain stimulation [17]. Attention is a complex cognitive function that involves creating a selective processing focus. This encompasses a spectrum of cognitive faculties, which encompass tasks such as orienting to sensory stimuli, sustaining a state of vigilance, and orchestrating mental functions necessary to execute intricate daily activities [18].

Distinguishing between LDs and Attention Deficit Hyperactivity Disorder (ADHD) is essential due to their representation of distinct pathologies, albeit with the potential for comorbidity. While both conditions manifest cognitive impairments and present challenges within educational settings, they originate from different underlying mechanisms and call for tailored interventions. LDs primarily entail difficulties acquiring specific academic skills, such as reading, writing, and mathematics, without significant intellectual impairment or external factors accounting for the challenges. Conversely, ADHD predominantly manifests as deficits in attention regulation, impulse control, and hyperactivity, affecting various aspects of daily functioning beyond academic performance. Acknowledging the potential overlap and comorbidity between LD and ADHD is crucial for comprehensive assessment and intervention strategies [19]. Individuals may present with cognitive and behavioral challenges, necessitating multifaceted support. Clarifying these distinctions is imperative to ensure accurate diagnosis and appropriate interventions for affected individuals.

Impairments in executive functions, including working memory and attention, may lead to educational, social, and familial challenges. It is essential to address these problems with effective rehabilitation methods. LDs can lead to functional impairment, so early diagnosis and intervention can prevent various issues for those who suffer from them. Numerous studies have substantiated the beneficial outcomes of interventions that enhance executive functions, encompassing working memory and attention [20, 21]. Recognizing the positive results of such rehabilitation, the American Society of Psychology has approved neurofeedback as a rehabilitation method for LDs [22, 23].

Neurofeedback essentially involves actively conditioning the electrical activity in the brain [24]. Brain waves are classified into five categories based on frequency, with Delta (less than 4 Hz), Theta (4 to 7 Hz), Alpha (8 to 13 Hz), Beta (14 to 30 Hz), and Gamma (greater than 30 Hz) being the highest and fastest categories [25]. The majority of researchers have directed their attention toward distinct neurofeedback protocols as a means to enhance cognitive performance [26]. These protocols encompass neurofeedback rehabilitation interventions designed to modulate specific electroencephalogram (EEG) aspects, including theta, alpha, alpha/theta ratio, beta, and gamma training [27]. Nevertheless, the results of this frequency-based rehabilitation have exhibited variations across different studies [28].

Individuals who received theta (4-7 Hz) augmenting neurofeedback experienced a slower radar detection performance. In contrast, those who received theta-suppression rehabilitation had an increase in their radar detection performance [29]. Elevated theta activity, especially within the left parietal-occipital region (sites O1 and P3), has been linked to reduced arousal levels [30]. Nonetheless, in contrast to attempts to suppress theta activity in posterior brain regions to improve sustained attention, numerous investigations have established a positive relationship between theta band synchronization (i.e., increased power) and favorable cognitive performance. Enhanced theta band power has proven conducive to strengthening working memory, episodic memory, and encoding new information [31]. The frontal midline (fmh) region exhibits prominent theta band activity in brain activity, consistently associated with attributes such as focused attention, concentration, and creativity. This phenomenon is often indicative of the effects of meditation [32]. For alpha band activity, investigations have highlighted two distinct ranges: the upper alpha band (9.5-12 Hz) has been linked to semantic memory processes [33] and the retrieval of information from long-term memory [34], while the lower alpha band, encompassing alpha 1 (6-8 Hz) and alpha 2 (8-10 Hz), is strongly associated with attentional processes [35]. Notably, participants with neurofeedback training to enhance upper alpha band power, particularly with open eyes, demonstrated improved performance in mental rotation tasks. Beyond alpha neurofeedback, a rehabilitation protocol has also been developed, focusing on modulating the alpha/theta ratio [36].

Pérez-Elvira et al. [37] researched children with LDs. They found that alpha/theta neurofeedback improved their behavior and brain wave patterns, with effects persisting even after a two-month follow-up. Previous research has presented evidence of the benefits of employing the alpha-theta protocol on behavioral and cognitive functions. These effects encompass slower hyperactivity [27], heightened concentration and academic achievement [38], enhancements in attention-related metrics [39], and the long-term augmentation of working memory. Most of these investigations have employed single-subject research designs to assess the impact of neurofeedback on attention and working memory.

The proposed alpha/theta neurofeedback protocol holds promise as an intervention for children with learning disabilities (LDs), particularly in addressing attention and working memory deficits. The rationale for applying neurofeedback lies in the neurobiological underpinnings of LDs, which often involve aberrant patterns of brain activity, including heightened theta power and diminished alpha power. Alpha activity, particularly in the upper alpha band, is associated with attentional processes and retrieval from long-term memory. In contrast, theta activity has been linked to arousal levels and cognitive functions such as working memory [40]. These abnormal neural signatures contribute to mental impairments, such as difficulties in attentional control and working memory maintenance, which are central to academic performance. Through neurofeedback, individuals can learn to modulate their brainwave patterns, potentially improving attention regulation and working memory capacity. It is possible to influence the neural mechanisms implicated in LDs via the alpha and theta frequency bands. Existing research has demonstrated the efficacy of alpha/theta neurofeedback in improving behavioral and cognitive functions in various populations, including individuals with attention deficits and hyperactivity. However, there remains a gap in the literature regarding its specific application to children with LDs. To contribute to the existing knowledge, we aimed to investigate the effects of alpha/theta neurofeedback rehabilitation on the attention and working memory of female students with LDs. Expanding this research could increase its generalizability and benefit both research and clinical settings. By elucidating the potential benefits of this intervention, we seek to contribute to both theoretical understanding and practical interventions for children facing challenges associated with LDs.

2. Materials and Methods

Within the framework of this quasi-experimental investigation, two distinct groups were considered: one designated as the experimental group and the other as the control group. The research was identified by the code IR.SBU.REC.1400.265, obtained ethical approval from the Ethics Committee of Shahid Beheshti University.

2.1 Study Participants

The research population encompassed all female students in the second, third, and fourth grades referred to specialized LDs' centers in Tehran during the 2020-2021 academic year. For this study, we employed a convenience sampling method to select 40 female students experiencing learning difficulties from a larger pool of individuals referred for evaluation by clinical psychologists. Two groups were formed through random assignment: the neurofeedback experimental group (n = 20), which received alpha/theta neurofeedback, and the control group (n = 20). Nonetheless, three students withdrew from the control and experimental groups. As a result, the final analysis was carried out on 17 participants in the neurofeedback experimental group (n = 17) and 17 participants in the control group (n = 17) (Figure 1). Throughout the study, attrition affected both the experimental and control groups, with three participants withdrawing after randomization. These dropouts occurred due to scheduling conflicts, where the participants could not attend the required sessions, and a waning of interest or motivation as the study progressed, particularly noted during the follow-up phase. Although reasons for withdrawal were not always explicitly articulated, it is inferred that the demanding nature of the neurofeedback training and potential personal or undisclosed reasons contributed to the attrition. The dropouts in the control and experimental groups did not show a significant number discrepancy, suggesting a non-differential dropout effect. The final analysis included only those who fully engaged with the study protocol, which allowed for a focused evaluation of neurofeedback's effectiveness but also highlighted the need for flexible scheduling and motivational strategies in future research to reduce the likelihood of participant withdrawal.

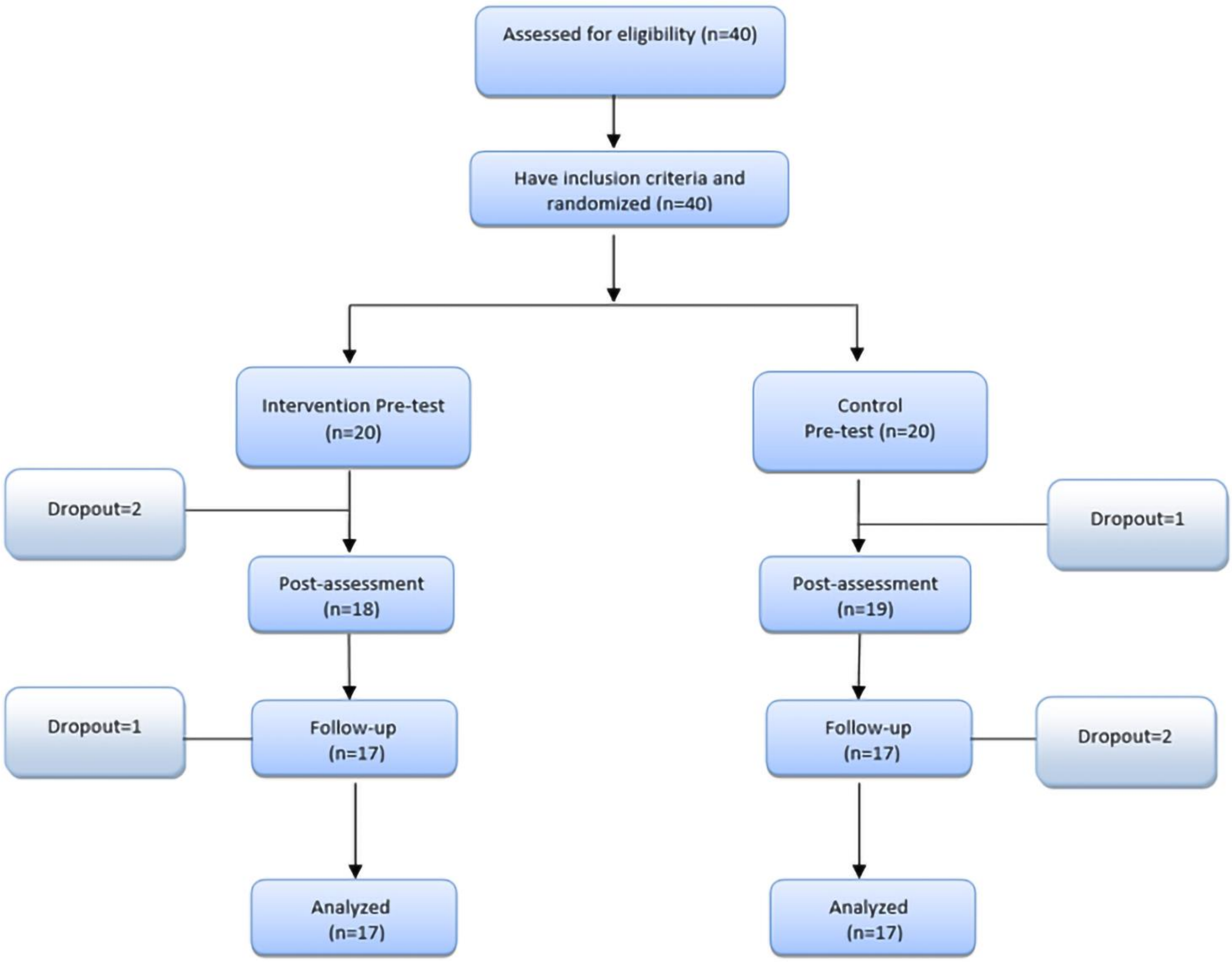

Figure 1 Consort flow chart for the recruitment process.

Inclusion in this research study required students to fulfill specific criteria. These criteria encompassed: (1) completion of a standard neurological and psychiatric assessment, excluding diagnostic prerequisites for LDs; (2) Attainment of a minimum score of 85 on the Wechsler Intelligence Scale for Children 4th Edition (WISC-4), excluding individuals with intellectual disabilities; (3) maternal education at least at a secondary level and a household income equivalent to or exceeding 50% of the minimum wage, or equivalent caregiver education and income if the mother was unavailable ; (4) standard EEG alpha/theta ratio compared to age-matched normative databases. The criteria for elevated alpha/theta ratio were removed to avoid exacerbating existing abnormalities; (5) absence of psychotic or bipolar disorders; and (6) possession of the necessary physical and cognitive capacity to engage in rehabilitation sessions. The last inclusion criterion was added because female students with LDs exhibit more theta power and less alpha power in their EEG than female students with typical development. Participants who missed two rehabilitation sessions or expressed dissatisfaction with their participation were excluded from the study. The methods used in this study are consistent with the ethical standards of the National Research Committee, the Helsinki Declaration of 1964, subsequent revisions, or equivalent ethical standards. We obtained written informed consent from all participants and their parents/legal guardians, and the researchers maintained complete confidentiality. No charges were imposed on participants at any stage of the research.

The determination of LDs relied on a three-fold set of criteria: (a) underachievement in academic performance, as attested by teachers and parents, (b) clinical diagnosis by a psychologist by criteria in the DSM-5 [41], and (c) written informed consent provided by the participants and their parents/legal guardians before the interview. Pre-tests were conducted after the primary individual and group assessments, which included the n-back Task and Stroop tests.

2.2 Neurofeedback Rehabilitation

We explained the rehabilitation procedure and timeline to the participants before commencing rehabilitation. The experimental group underwent a two-month rehabilitation plan consisting of 20 sessions at a rate of two per week, followed by a 60-day follow-up period. We used a delta domain determination window to prevent participants from dozing off during the corresponding settings. The room maintained constant sound and lighting levels. We utilized the ProCamp 5 device manufactured by Thought Technology in Canada, which features a sampling sensitivity of 256 Hz. The software interface provided precise control over the neurofeedback protocols, enabling real-time monitoring and adjustment of alpha and theta waves. In the alpha/theta neurofeedback rehabilitation sessions, electrodes were meticulously positioned on the scalp and earlobes following the internationally recognized 10-20 system. The study employed neurofeedback rehabilitation sessions (resting-EEG) where participants engaged in deliberate relaxation, controlled breathing, and visualization of positive memories. Electrodes were placed on the scalp and earlobes following the international 10-20 system, and participants were exposed to auditory feedback, including sounds resembling river and ocean waves. This setup aimed to modulate alpha and theta waves during relaxation with closed eyes. Specifically, we placed the anode electrode over the central cortex (Cz area) for Sensory Motor Rhythm (SMR) stimulation, while the cathode electrode was positioned on the earlobes. This placement aimed to facilitate optimal engagement with the neurofeedback protocol, enhancing participants' ability to regulate brainwave activity effectively. During the sessions, participants engaged in a deliberate process of muscle relaxation, controlled breathing, and visualization of positive memories while receiving auditory feedback. The auditory stimuli, including river and ocean wave sounds, were carefully selected to correspond with the desired brainwave frequencies, amplifying alpha and theta waves for enhanced cognitive modulation. This involved applying the alpha-theta protocol [28] for 20-25 minutes alongside an osmosis range of 10-20. The neurofeedback protocols utilized in each session were centered on Sensory Motor Rhythm (SMR) within the Cz area (central cortex) [42]. The primary objective of implementing the alpha/theta protocol during a state of relaxation with closed eyes was to amplify theta wave activity while maintaining or slightly decreasing alpha wave activity, thereby increasing the ratio of theta waves (4-8 Hz) to alpha waves (8-12 Hz) in the mid and frontal brain regions. This strategic approach stemmed from the observed lower baseline activity of theta waves compared to alpha waves in the brain. Thus, the aim was to rebalance the ratio between these two types of brain waves towards a state associated with enhanced cognitive modulation and attentional processes [43].

In the neurofeedback sessions, participants in the experimental group were directed to engage in deliberate muscle relaxation, breathing regulation, and closing their eyes. In adherence to established rehabilitation protocols, the placement of electrodes on their scalp and earlobes was meticulously executed according to the 10-20 international system [44]. Participants were tasked with deliberately recollecting positive memories while simultaneously being exposed to an auditory feedback regimen, which included sounds resembling the gentle ebb and flow of river waves, the soothing rhythm of ocean waves, and a subtle background auditory backdrop. River waves are associated with enhanced alpha waves, while ocean waves amplify theta waves in the cerebral cortex [45].

To activate alpha waves (related to river waves), participants periodically listened to river and ocean waves while using mental imagery to hear the ocean sound more clearly and loudly, boosting their theta waves. During the sessions, we monitored the electrodes for 90 seconds with both open and closed eyes, collecting data at four additional points (P3, P4, O1, O2) using the active electrode. After removing artifacts from the data, we calculated the alpha frequency for each participant using independent component analysis (ICA) to remove embedded artifacts, such as muscle movements, eye blinks, and eye movements, without deleting the affected portions of the data [46].

2.3 Measures

2.3.1 The N-back Task

Participants completed three versions of the n-back working memory task: verbal, spatial, and ordinary objects. In all versions, participants identified stimuli as '2-back' when new stimuli appeared. In the verbal task, lowercase letters in Courier New font (font size 72) were displayed at the center of the screen, with vowels excluded. The spatial version used a 3 cm diameter black circle that moved around in a 4-row by a 5-column array, mimicking the setup of the verbal task. For the standard object version of the experiment, a set of 20 images closely resembling those in Snodgrass & Vanderwart in 1980 [47] were sourced from the International Picture Naming Project, available on the website of the Centre for Reading and Language, University of California San Diego [48]. Careful images were selected to ensure they met Snodgrass and Vanderwart's criteria for naming agreement, familiarity, complexity, imagery assessments, and naming latencies [49]. The objects selected aimed to maintain equitable representation across semantic categories, encompassing items such as fruits, vegetables, furniture, and modes of transportation. A deliberate effort was made to achieve a balanced distribution of objects categorized as "male," "female," and "neutral" [50]. Dependent measures for the n-back task included the number of correct responses and the average reaction time.

2.3.2 Stroop Test

This describes the Stroop test, a classic method for evaluating selective attention in children's performance. McLeod first developed the test in 1996 [51], and it involves three stages:

A. In the first stage, known as 'stage of coordinated efforts,' names of four fundamental colors are presented in black at the screen’s center. Participants must respond promptly by selecting one of the keys corresponding to the color names: blue, red, yellow, or green on the keyboard.
B. In the second stage, names of the same four primary colors are presented in their corresponding hues, requiring participants to swiftly press the key that matches each color on the keyboard.
C. In the third stage, called the stage of awkward attempts or interference, the names of the primary colors appear on the screen in colors different from their name. The participant must swiftly press the key on the keyboard corresponding to the color of the displayed word. The

test measures two indicators: Accuracy (number of correct responses) and Reaction Time (average response time in milliseconds). The reliability of the Stroop test has been confirmed in various studies [52].

2.4 Statistical Analysis

Repeated measures ANOVA was conducted at three different time stages to assess both groups, while mixed repeated measures ANOVA was used to compare the performance of two distinct groups. We conducted an independent samples t-test to determine age differences between the neurofeedback experimental and control group participants. Using SPSS-26 statistical software, we employed the Chi-square test to examine specific demographic factors, such as birth order and father's job status, for a comparative analysis between the two groups.

3. Results

No significant differences in demographic variables, such as age, father's job status, and age characteristics, were observed between the two groups (Table 1).

Table 1 Comparisons of Demographic Characteristics across Groups.

Variables	Neurofeedback (n = 17)	Control (n = 17)	Statistical Analyses
Father's job Status (unemployed/part-time/employed)	0(0%)/7(41.2%)/10(58.8%)	1(5.9%)/5(29.4%)/11(64.7%)	$\chi^2(2) = 1.38$, p = 0.50
Birth order (first/second/third)	13(76.5%)/4(23.5%)/0(0%)	15(88.2%)/2(11.8%)/0(0%)	$\chi^2(2) = 1.27$, p = 0.53
Age years (S.D)	14.32(1.09)	14.87(1.32)	t(32) = 1.32, p = 0.20

Note: Values are presented as counts (percentages) for categorical variables and mean (standard deviation) for continuous variables. P-values denote statistical significance.

Based on Table 1, the mean age of participants in the experimental group was 14.32 years (SD = 1.09), while in the control group, it was 14.87 years (SD = 1.32). The father's job distribution in the experimental group was as follows: unemployed (0), part-time job (7), and employed (10); in the control group, it was unemployed (1), part-time job (5), and used (11). Table 2 presents descriptive statistics of the Stroop test, including Correct Accuracy and Reaction Time, and the n-back test, which includes Correct Response and True Response Time, for both the Neurofeedback and Control groups.

Table 2 Summary of pre-, post-rehabilitation, and 2-month follow-up assessment.

Variable	Group	Pere test	Post-test	Follow-up
STROOP; Correct Accuracy	Control	65.53 (8.71)	66.65 (8.93)	66.71 (8.90)
	Experimental	68.82(9.18)	76.35(9.24)	75.82(9.87)
STROOP; Reaction Time	Control	4.35 (0.94)	4.07 (1.01)	4.10 (0.99)

	Experimental	4.72(0.89)	2.62(0.89)	2.67(0.87)
n-back; Correct Response	Control	57.24 (5.78)	57.76 (5.16)	57.41 (5.32)
	Experimental	58.59(7.00)	62.76(6.81)	63.12(7.14)
n-back; True Response Time	Control	2.30 (0.51)	2.18 (0.38)	2.25 (0.41)
	Experimental	2.47(0.49)	1.97(0.38)	2.00(0.35)

Legends: Mean (Standard Deviations).

Mauchly's sphericity test indicated that sphericity was significant for Correct Accuracy, Reaction Time, and True Response Time ($p < 0.05$) and not important only for Correct Response ($p > 0.05$). Therefore, the sphericity assumption was used for Correct Accuracy, Reaction Time, and True Response Time. In contrast, the Greenhouse-Geisser test was used for the Correct Response variable ($p > 0.05$). Levene's test indicated non-significance for all variables, affirming the homogeneity of between-group variances. The Box's M test confirmed the homogeneity of variance-covariance matrices.

We conducted repeated measures ANOVA to compare neurofeedback and control groups on correct accuracy. The between-subjects factor was group (neurofeedback vs. control), and the within-subjects factor was assessment time (pre-rehabilitation, post-rehabilitation, and follow-up). Although we observed similarities between the groups during the pre-test in Correct Response, we found significant differences between the groups in correct accuracy [$F (1,32) = 5.64$, $p < 0.001$, $\eta^2 = 0.15$] and in between-subjects by within-subjects interaction effect (TIMEGROUP) [$F (2,64) = 28.56$, $p < 0.001$, $\eta^2 = 0.47$] and the within-subjects effect of time [$F (2,64) = 53.76$, $p < 0.001$, $\eta^2 = 0.63$]. Significant differences between neurofeedback and control groups were also observed in STROOP reaction time [$F (1,32) = 9.04$, $p < 0.001$, $\eta^2 = 0.22$] and interaction effect (TIMEGROUP) [$F (2,64) = 28.87$, $p < 0.001$, $\eta^2 = 0.47$] and the within-subjects effect of time [$F (2,64) = 47.00$, $p < 0.001$, $\eta^2 = 0.60$] (Table 3 & Figure 2).

Table 3 Summary of per-, post-rehabilitation, and 2-month follow-up and Mixed repeated ANOVA.

Variable	Group	Sum of Squares	df	Mean of Squares	F	P	Eta
STROOP; Correct Accuracy	Time	401.90	1.35	297.78	53.76	0.001	0.627
	Experimental *Time	213.54	1.35	158.22	28.56	0.001	0.472
	Experimental	1386.03	1	1386.03	5.64	0.024	0.15
STROOP; Reaction Time	Time	30.90	1.11	27.87	47.99	0.001	0.600
	Experimental *Time	18.59	1.11	16.76	28.87	0.001	0.474
	Experimental	17.77	1	17.77	9.0	0.005	0.220
n-back; Correct Response	Time	125.49	2	62.74	26.01	0.001	0.448
	rehabilitation *Time	92.78	2	46.39	19.23	0.001	0.375
	Rehabilitation	412.01	1	412.01	3.65	0.032	0.11
	Time	1.854	1.177	1.575	22.127	0.001	0.409

n-back; True Response Time	rehabilitation *Time	0.918	1.177	0.780	10.951	0.001	0.255
	rehabilitation	0.225	1	0.225	0.484	0.491	0.015

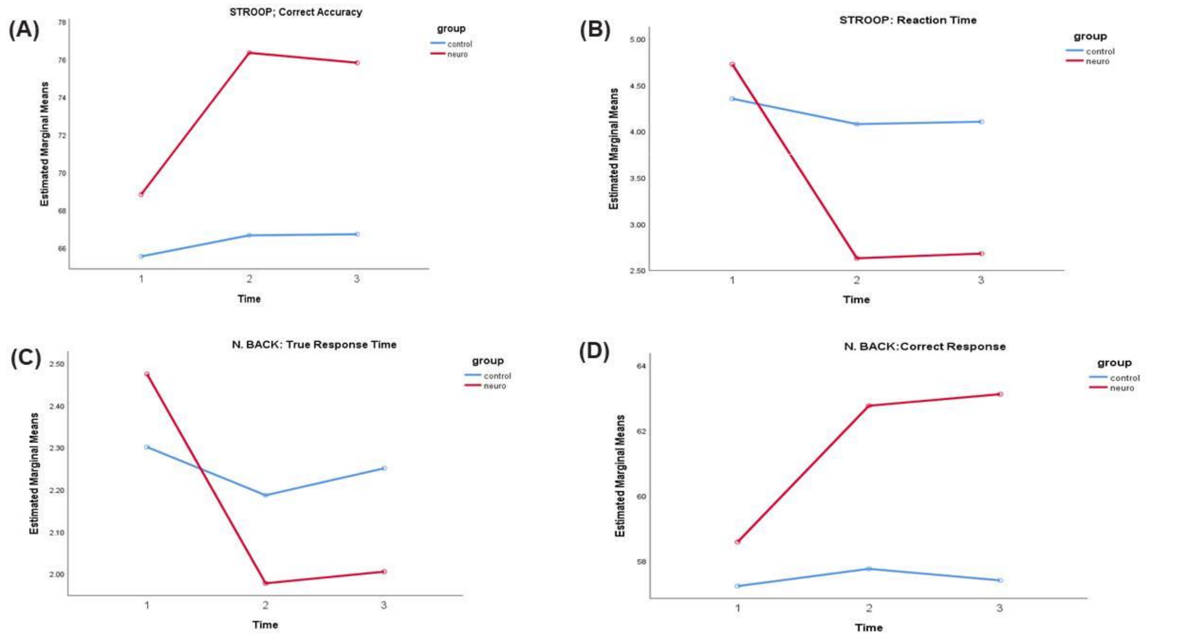

Figure 2 (A) Interaction between time and group in STROOP, Correct Accuracy; Figure **(B)** Interaction between time and group in STROOP, Reaction Time. **(C)** Interaction between time and group in n-back, Correct Response, and **(D)** Interaction between time and group in n-back, True Response Time.

We employed repeated measures analysis of variance (ANOVA) to scrutinize disparities between the neurofeedback experimental group and the control group concerning the various components of the n-back task. While similarities were observed between the groups in Correct Response during the pre-test, significant differences were found between the neurofeedback and control groups in Correct Response [F (1,32) = 3.65, p < 0.001, η^2 = 0.11], and in the between-subjects by within-subjects interaction effect (TIMEGROUP) [F (2,64) = 19.23, p < 0.001, η^2 = 0.38] and the within-subjects effect of time [F (2,64) = 26.01, p < 0.001, η^2 = 0.45]. Concerning n-back True Response Time, no significant differences were observed between the neurofeedback and control groups [F (1,32) = 0.48, p = 0.49, η^2 = 0.015]. However, significant differences were found in the between-subjects by within-subjects interaction effect (TIMEGROUP) [F (2,64) = 10.95, p < 0.001, η^2 = 0.26] and within-subjects effect of time [F (2,64) = 22.12, p < 0.001, η^2 = 0.41] (Table 3 & Figure 2).

The independent t-test for comparing rehabilitation and control groups in the pre-test showed no significant differences in the measured variables between the two groups. However, vital differences emerged between the groups in the post-test and follow-up stages. The experimental group exhibited significantly higher mean scores for Correct Accuracy and Correct Response than the control group. In the post-test and follow-up stages, the experimental group's reaction time and accurate response time mean scores were significantly higher than control group (Figure 3).

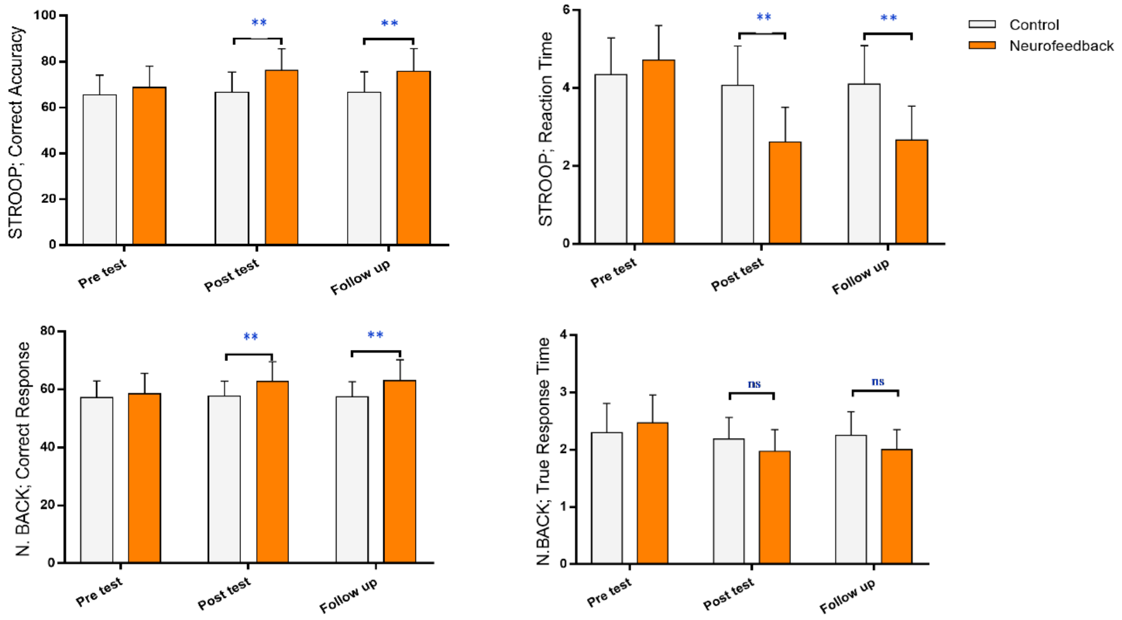

Figure 3 Comparison of variables in rehabilitation (neurofeedback) and control groups at different time stages.

4. Discussion

This investigation aimed to assess the effects of Alpha/Theta Neurofeedback rehabilitation on attention and working memory in female students with LDs. The results disclosed that following two-month neurofeedback rehabilitation, there was notable augmentation in attention, characterized by accuracy and reaction time improvements. Enhancements were observed in working memory, denoting increased correct responses and the time taken to respond appropriately among female students with LDs. These advancements persisted throughout the subsequent two-month follow-up period.

An investigation by Pérez-Elvira et al. [37] revealed that students diagnosed with LDs exhibit heightened slow-wave activity within their EEG patterns. More specifically, they demonstrated elevated theta activity and reduced alpha activity compared to their non-LD counterparts of the same gender. Research has delved into the interplay of alpha and theta wave interactions within cohorts afflicted by LDs, reading and writing impairments, and dementia, lending support to this perspective. Ranges of neurological functions have been associated with heightened theta and delta power alongside diminished alpha power levels. This study employed alpha/theta rehabilitation protocol at CZ points to evaluate the participants' progress. The rehabilitation was based on the following rationale: A) Students with LDs are more likely to display increased theta activity in their EEGs than non-LD students of the same age [53]. B) Sufficient silent alpha activity is an essential prerequisite for effectively executing cognitive tasks within the domains associated with academic assignments, encompassing typical students and adults [54]. These results imply that lowering the alpha/theta ratio in the EEGs of students with LDs may facilitate normalizing their EEG patterns, potentially augmenting their cognitive and behavioral functions [22]. This study provides evidence that neurofeedback leads to enhancement in working memory, findings that are consistent with prior research [26, 55]. To elucidate this discovery, it is postulated that neurofeedback-based rehabilitation administered at the Cz focal point exerts simultaneous influence over the sensory-motor, motor, and cingulate cortices. Situated at the confluence of the parietal and frontal lobes, the sensory-motor cortex wields extensive influence. Hence, it comes as no surprise that early pioneers in the field of Neurotherapy initiated the rehabilitation procedure within this cortical realm [56].

The sensory-motor cortex encodes physical and cognitive functions within the brain, with the neural circuits governing mental processes mirroring those orchestrating physical actions. The sensory-motor cortex is pivotal in regulating both bodily and cognitive processes. For therapists encountering challenges in comprehending the logical sequence of mental tasks, neurofeedback rehabilitation targeting the left hemisphere (C3) may yield potential benefits [16].

Rehabilitation targeting the sensory-motor cortex of the right hemisphere, specifically at the C4 location, can elicit various emotional responses, induce relaxation, or provoke excitement. In contrast, rehabilitation can yield a combination of reactions when applied to the intermediate point (CZ). The neurofeedback rehabilitation focused on CZ can simultaneously influence three critical areas: the sensory-motor cortices, the motor cortex, and the cingulate cortex. These regions play pivotal roles in regulating emotions, attention, and working memory, serving as vital resources for external actions, such as physical movement, and internal cognitive processes, including thinking and reasoning [57]. These align with the findings reported by Escolano, Aguilar, & Minguez in 2011 [58], who investigated the effects of neurofeedback rehabilitation centered on the high alpha band's impact on working memory. Alternatively, these outcomes may be attributed to the augmentation of the sensorimotor rhythm (SMR) in the CZ region, which activates the neural circuitry associated with working memory. Prior research has posited that working memory relies on the neural network formed through the interaction between the attention control systems located in the prefrontal cortex and the storage of sensory information within the posterior communication cortex.

The conditioning theory of learning explains the changes observed in neurofeedback. Modifying brain waves, signaled by a predetermined criterion, such as a change in the amplitude of brain waves, can lead to learning when accompanied by a desired outcome, such as the movement of video images or sound production. Neurofeedback rehabilitation provides external stimuli to reinforce this learning process and promote positive behavior change. This behavior change is primarily due to changes in the brain waves, making neurofeedback an effective rehabilitation method for various behavioral conditions by linking changes in behavior to changes in brain waves.

To explain the finding that reducing slow brain waves or increasing brain wave "skirts" can improve mental function, it is crucial to acknowledge the role of slow brain waves (Theta) in cognitive impairments, including daydreaming, distractibility, and lack of concentration, slow reaction time, and poor judgment. Children with LDs often exhibit increased Theta activity during rest and attentional tasks. Excessive slow waves in different brain regions are associated with impaired impulse control, reduced attention, and low arousal. Reducing or suppressing slow waves can lead to behavior changes, particularly student attention, as observed in previous research [59]. Neurofeedback is a method that can train students to shift their attention from internal to external stimuli, leading to improved performance.

Changes in behavior can sometimes be observed even when there is no measurable change in brain wave levels. Engaging in techniques to influence brainwave activity, such as neurofeedback, can result in discernible shifts in brain function. After rehabilitation, any alteration in the brain's electrical activity can result in the reorganization of the entire bioelectrical system, leading to a natural reflexive normalization response in the brain. As a result, the relationship between brainwave changes and behavioral changes is not always linear or bidirectional, and one can result in apparent differences from the other. Although the mechanisms behind these brain changes are not yet fully understood, we can still observe and measure the changes in behavior. Our research demonstrates that alpha/theta neurofeedback can effectively train the brain to regulate attentional focus, leading to sustained attention and working memory improvements. This suggests a potential paradigm shift in educational and clinical settings, where such interventions can be applied as targeted support for this demographic. The applicability of our findings extends beyond theoretical research and holds promise for integration into real-world therapeutic programs, providing a blueprint for custom-tailored cognitive rehabilitation strategies.

This study has identified several limitations, encompassing both actual and potential constraints. While practical, this study concedes that the chosen convenience sampling strategy may not be indicative of the broader population with learning disabilities. We acknowledge that this sample selection method inherently limits the generalizability of our findings. The inherent interest of participants in neurofeedback, signifying a potential self-selection bias, could have contributed to the positive outcomes observed. These considerations underscore the necessity for future research to employ more rigorous, randomized sampling methods to ensure a representative demographic, fortifying the validity of the findings.

Moreover, an emphasis on longitudinal studies would be beneficial to ascertain the sustained effects of neurofeedback over a more extended period, addressing another vital aspect raised by the review. This study did not control for external factors affecting cognitive function, such as participants' sleep quality, dietary habits, and physical activity levels, which could introduce confounding variables affecting attention and working memory assessments. Future studies must monitor and report these potential confounders to better isolate the neurofeedback intervention's effect. The study's reliance on specific cognitive tasks to assess improvements may not fully reflect everyday cognitive challenges encountered by individuals with learning disabilities. Therefore, future research should consider integrating ecological validity into their design by including real-world tasks or simulations that more accurately represent these individuals' daily cognitive demands. These enhancements in research design will contribute to a more nuanced understanding of neurofeedback's role in cognitive enhancement and its practical implications for educational strategies.

Several recommendations can enhance the scope and robustness of future research in this domain. Researchers should consider broadening their participant base by including male and female students with LDs. This approach will enhance the generalizability of findings and provide a more holistic understanding of the effects of alpha/theta neurofeedback rehabilitation. It is recommended that future research incorporate more extended follow-up periods to capture potential long-term effects of Alpha/Theta Neurofeedback Rehabilitation, enhancing our comprehension of its sustained impact on attention and working memory in students with LDs. Researchers are strongly encouraged to substantiate the findings of this research by conducting cross-age group comparative studies. Such endeavors would significantly enrich our comprehension of the utility and efficacy of neurofeedback rehabilitation across diverse educational settings and demographic groups. In addition, future investigations should explore the intricate neural mechanisms at a deeper level, and this can be accomplished by integrating advanced neuroimaging techniques like functional magnetic resonance imaging (fMRI) and positron emission tomography

(PET) scans. The application of these cutting-edge imaging technologies has the potential to unveil nuanced alterations within neural pathways that occur throughout neurofeedback protocol, offering enhanced insights into the neurobiological foundations of this therapeutic modality.

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