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The Effectiveness of Neurofeedback Training on EEG Coherence and Neuropsychological Functions in Children With Reading Disability

Mohammad Ali Nazari[1], Elnaz Mosanezhad[1], Tooraj Hashemi[1], and Ali Jahan[1,2]

Abstract

Neurofeedback training (NFT) is an effective intervention in regulating electroencephalogram (EEG) abnormalities leading to improvements in behavioral deficits, which exist in children with reading disabilities. This single-subject study explores our evaluation of the improvements in the reading ability and phonological awareness deficit, as well as the changes in the EEG in children with reading disabilities as a result of NFT. Participants were 6 children, aged between 8 and 10 years, who completed twenty 30-minute sessions of NFT and follow-up measurement sessions 2 months subsequent to the completion of the training sessions. The results showed significant improvement in reading and phonological awareness skills. Furthermore, EEG analysis did not show notable changes in the power of the targeted bands (delta, theta, and beta), rather there was normalization of coherence of the theta band at T3-T4, delta band at Cz-Fz, and beta band at Cz-Fz, Cz-Pz, and Cz-C4. These significant changes in coherence possibly indicate integration of sensory and motor areas that explains the improvements in reading skills and phonological awareness.

Keywords

neurofeedback training, reading disability, phonological awareness, coherence

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Introduction

Reading disability is defined as a significant discrepancy between an individual's reading achievement and his or her ability based on intelligence, education, and age.[1] Children with reading disability have difficulties in acquiring letter–speech sound associations and also in recognizing and manipulating the sound structure of language, an ability referred to as phonological awareness.[2] It is assumed that the planum temporale (PT) and Heschle gyrus are involved in phonological awareness, where auditory phonemes could be mapped into visual graphemes.[3] Blau et al[4] observed underactivation of the superior temporal gyrus in people with dyslexia for the integration of letter–speech sound. The reduced integration is associated with a deficit in auditory processing and phonological awareness. Larsen et al studied the PT in normal and dyslexic participants using magnetic resonance imaging (MRI). They found that participants with dyslexia (70%) had high frequency of PT symmetry, whereas it was in only 30% of the control group. Patients with dyslexia with PT symmetry had phonological deficits in reading, indicating PT is involved in language processing. Their finding also showed that the right PT is larger in patients with dyslexia. Another study by Brown et al[6] showed decreased gray matter density of the temporal lobe (around T3). Some other studies supported these findings.[7-9]

While focusing on the brain regions related to language processing, contrasts have been observed in brain structure and the electroencephalogram (EEG) in children with reading disabilities.[10] For example, Arns et al[11] reported that children with dyslexia have increased slow activity (delta and theta) in the frontal and temporal regions of the brain. Rippon and Brunswick[12] reported increased frontal theta activity during phonological tasks in children with dyslexia. Dysfunction in the left superior temporal gyrus (T3) was also reported by Simos et al.[13] In some dyslexia studies, EEG coherence has been used

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as a quantitative measure of linear dependency between 2 distant brain regions. Sklar et al[14] showed higher intrahemispheric coherence and lower interhemispheric coherence in children with dyslexia. Shiota et al[15] showed increased inter- and intrahemispheric coherence in rest condition in children with dyslexia. Weiss and Muller[16] concluded that despite some controversies in coherence studies on dyslexia, a reduced coherence could be found in people with dyslexia.

For remedial purposes, some researchers tried to normalize the EEG (and consequently behavioral and cognitive deficits) via neurofeedback training (NFT) in children with learning disabilities (LDs).[17,18] Neurofeedback training is a form of operant conditioning, in which the electrical brain activity is rewarded or repressed.[19] Neurofeedback as an intervention has been useful in the treatment of disorders such as epilepsy,[20] attention-deficit hyperactivity disorder (ADHD),[21] and LDs.[22]

Thornton and Carmody[23] indicated that there is not sufficient research on NFT, especially regarding reading disorders. However, NFT studies of children with LDs have indicated an improvement in reading ability. For example, Fernandez et al[22] gave 20 sessions of NFT to 10 LD children, who had high ratios of theta-to-alpha absolute power (theta/alpha). Positive behavioral changes and significant improvements in cognitive performances were found, which was not present in the control group. Follow-up after 2 years indicated that the behavioral changes continued in the experimental group, and in contrast, EEG maturational lag increased in the control group.[24] Thornton and Carmody[23] reported the effect of NFT on a 9-year-old girl with history of learning problems. After completing 40 sessions of NFT, her auditory memory and reading memory had improved. Other research demonstrated the enhancement of reading scores of a 17-year-old adolescent after NFT.[23] In another single-case study, Jacobs[25] demonstrated the positive effect of NFT on 2 boys with learning, attention, mood, social, and developmental deficits. Some studies have also reported positive effects of NFT on working memory and attention, which are essential components of reading ability.[26-28] Using NFT on 10 children with dyslexia, Breteler et al[29,30] found a small improvement in their spelling skills, but no improvement in their reading abilities.

As noted above, most of the studies on NFT have been focused on children with LDs, and there is not sufficient research to investigate the effectiveness of NFT on children with reading disorders. This study evaluates the effectiveness of NFT on children with reading disabilities and difficulty in phonological awareness.

Methods

Participants

Six male children with dyslexia with a mean age of 8 to 10 (mean = 9 and standard deviation [SD] = 0.63) and average intelligent quotient (IQ) of 101.5 (SD = 12.95), who had no history of brain injury, neuropsychological or psychiatric disorders, were selected from the Learning Disability Center of Tabriz. Diagnosis of reading disorder was confirmed by the Wechsler Intelligence Scale for Children (WISC-III) and Reading Disability Checklist.[31] The study was fully explained to parents, who then signed a consent form.

Measurements

To evaluate the effectiveness of NFT on reading ability at baseline and after the intervention, a reading disability test[30] was used. With this checklist, 2 scores were obtained for each participant: number of errors and reading length. A phonological awareness test[30] was given pre- and postintervention. Phonemes and syllables, discrimination and identification of the phonemes, phonetic segmentation, and phoneme deletion were evaluated.

The EEG was recorded in an eyes-closed resting condition using 19 surface electrodes (Electro-Cap, Eaton, Ohio, USA) based on the International 10-20 System. The EEG was amplified by NeuroScan (Herndon, Virginia, USA). DC-50 Hz was filtered and recorded with linked-ears reference at a sampling rate of 500 Hz. The impedance of electrodes was kept below 10 kΩ.

EEG signals were processed by NeuroGuide Delux (version 2.3.8). Artifact rejection was based on both visual inspection and computerized selection. Epochs were also visually analyzed by an expert, who determined the acceptance or rejection of each individual epoch. In total, 36 to 48 artifact-free EEG epochs (2.5 seconds) were selected for analysis. The EEG epoch time domain was then transformed into the frequency domain using a Fast Fourier Transformation (FFT) algorithm. The frequency bands were defined as delta (1-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), and beta (12-25 Hz). Absolute power, relative power, and coherence scores were calculated for each frequency band. Using NeuroGuide normative database, all power and coherence values were subsequently transformed into *Z* scores.

Procedure

The multiple baseline single-subject design included follow-up measurements after 2 months. To test the intervention, participants were randomly placed in 3 groups. After a stable and/or predictable pattern of performance was established for all baselines/groups (after 3 baseline measurements), the intervention was introduced to group 1. Then the intervention was applied to a second group (after 4 baselines). A third group was tracked without intervention. Therefore, we had 5 baselines for the last group.[32] During baseline (A phase), scores of reading ability, phonological awareness, and EEG were obtained. Treatment (B phase) involved 20 30-minute sessions of NFT, given two or three times a week. Measurements were made throughout the baseline (A) and treatment (B) phases. On completion of NFT, evaluations were repeated after 2 months.

NFT was conducted by Procomp Infiniti Encoder and Biograph Infiniti software (v 5.1.3). Training was set to decrease delta (1-4 Hz) and theta (4-8 Hz) and to increase beta (15-18 Hz) at T3 and F7, according to Rippon[12] and Arns.[11] For 12 sessions, all participants received the same NFT protocol only at T3. Then for 8 remaining sessions, the NFT protocol was administered to both T3 and F7. The length of NFT for T3 was 20 minutes and 10 minutes for F7. Training sessions were separated into a 2-minute baseline period (ie, no feedback), 30-minute feedback presentation, and a 2-minute baseline period again. Interactive video games were used as feedback for children.

Statistical Analysis

The data were evaluated for the target change by visual inspection of the graphs and clinical analysis. Mean percentage reduction (MPR) and mean percentage improvement (MPI) were calculated for clinical changes. There were no intergroup comparisons, the focus being on pretreatment versus posttreatment performance of each participant. The means, standard SDs, and Cohen *d* were also calculated for the baseline, treatment, and follow-up sessions of each participant. The Cohen guideline for the *d* statistic (0.2, 0.5, and 0.8 benchmarks for small-, medium-, and large-sized effects) was used.[33]

Results

Reading ability

Figure 1 shows the multiple baseline design used to assess changes in reading (A, number of mistakes; B, reading time) following the NFT in 3 groups. Figure 1A demonstrates a repeated pattern of reduction in the word reading mistakes following the intervention in all 3 groups. No major fluctuations are present in the data at other time points, suggesting the results are due strictly to the interventions. Although the second participant had an increase after 9 sessions, low scores were shown at the end of the interventions, and his scores remained well below his baseline scores at the follow-up assessment sessions. The participants showed the least amount of change at the follow-up assessments.

A similar pattern of changes was observed for the time that participants spent for reading (Figure 1B): all of the participants' scores remained constant over the baseline. Their scores were reduced only after the treatment was administered, although the reduction varied considerably between participants. At the follow-up sessions, the scores remained relatively constant.

Table 1 presents the following information for all 6 participants: mean, SD, MPR, Cohen *d* value at baseline, treatment, and follow-up assessments for all participants. The level of word reading mistakes is reduced in all participants and the reduction varies in magnitude from 4.65% to 44.54%. In comparing both the baseline treatment and the baseline follow-up phase, the values of effect sizes for all but 1 participant (participant 5) were large (above the 0.8). The effect size for participant 5 showed that treatment for this participant was not very effective. For time factor, the percentage of reduction ranged from 9.89 to 46.71 and all the effect sizes (between 1.19 and 3.13) were large (see Table 2).

Phonological Awareness

Figure 2 shows the phonological awareness scores at baseline, treatment, and follow-up assessments. Visual inspections showed that baseline levels remained relatively stable and an increase in scores is shown only after the introduction of NFT. A change in phonological awareness following intervention in one group doubled, while there was an absence of change in other groups who were yet to receive an intervention, which suggests that the changes occurred due to the treatment.

The MPI for phonological awareness ranged from 23.57 to 45.73. The mean level of phonological awareness scores was higher during the treatment and the follow-up phases, compared to the baseline period, indicating that a change in the behavior had occurred. The values of effect sizes for all participants were above 0.8 which indicates a large-sized effect (Table 3).

QEEG

Results revealed no important changes in the power of the signal of any aimed frequency band and recording channels. However, coherence analysis showed an interesting change toward normalization in delta, theta, and beta bands after NFT. Table 4 shows the statistics of *z* scored coherence in these frequency bands. The coherence of delta band in Fz-Cz was up trained from a lower than normal value to near normal. The pattern of changes in the theta band had a reduction of an abnormal hypercoherence toward near normal coherence between T3 and T4. The hypocoherence of beta band was approximated to normal in Fz-Cz, Cz-Pz, and Cz-C4 (Figure 3). Substantial remediation of abnormal coherence is better shown with brain maps in Figure 4.

Discussion

Analysis of behavioral data revealed an improvement in the reading ability by NFT in all participants. At the end of the treatment, participants showed a reduction in reading mistakes and reading time. The total Cohen *d* for the reading errors was 2.33 and 1.61 for reading time, suggesting a large improvement in both factors (Tables 1 and 2). Participants had better performance on phonological awareness test posttreatment. The Cohen *d* score was 1.44 for this variable, suggesting a large effect size (Table 3). Also, the follow-up assessment showed that behavioral improvements remained durable and better compared to those of the baseline phase.

Tansey and Bruner[34] reported the successful use of neurofeedback for academic and behavioral improvements by decreasing theta and enhancing beta. Furthermore, in some single-subject reports, Thornton and Carmody[23] reported improvements in reading, auditory memory, reading memory,

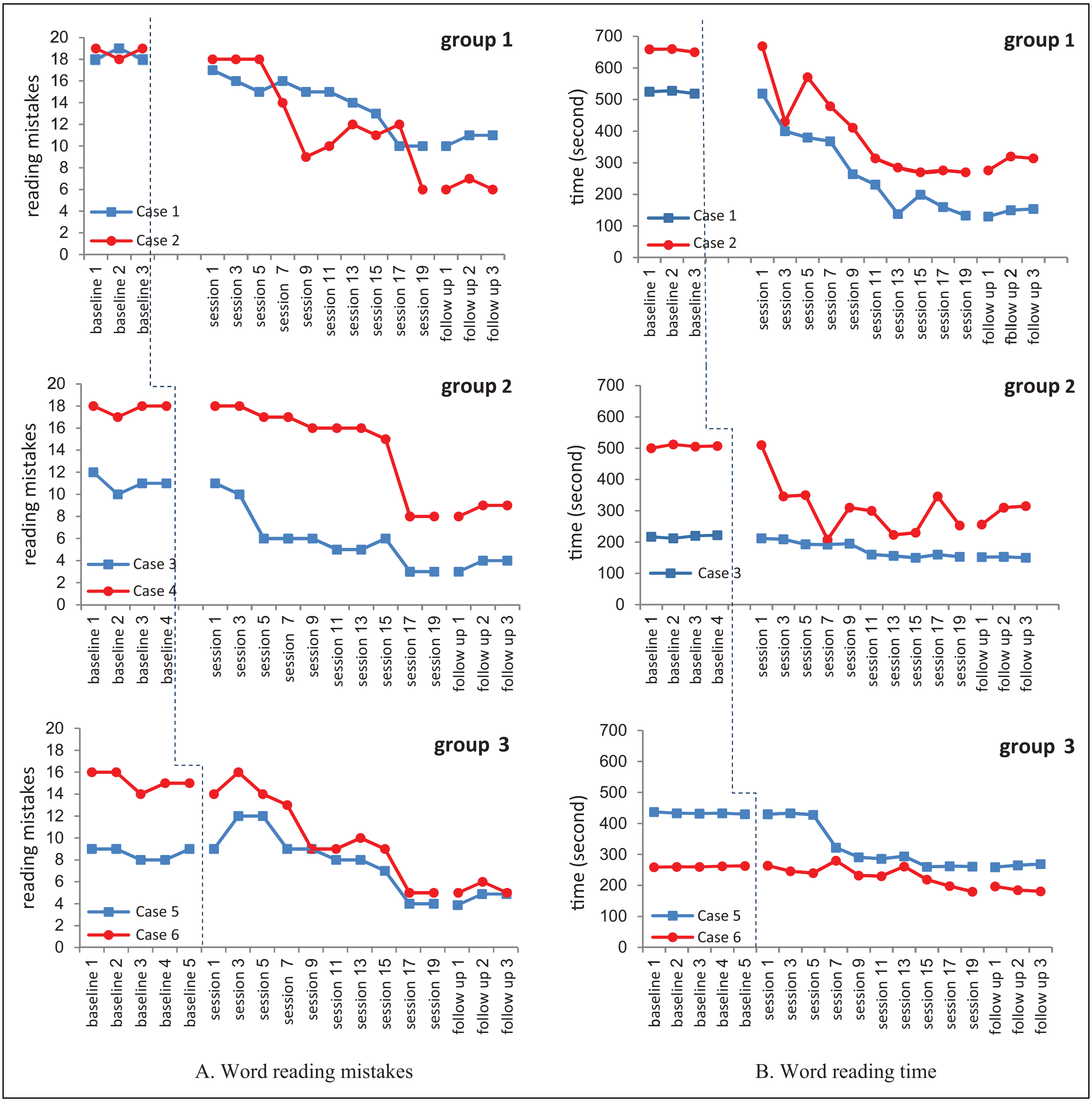

Figure 1. Pattern of reading ability changes across baseline, treatment, 1-week, 1-month, and 2-month follow-up assessments conducted for all 3 groups. A, Word reading mistakes. B, Word reading time.

Table 1. Mean and Standard Deviation of Word Reading Mistakes at Baseline, Treatment, 1-Week, 1-Month, and 2-Month Follow-Up Assessments

	MeanA1	MeanB	MeanA2	SDA1	SDB	SDA2	Cohen *d*, A1-B	Cohen *d*, A1-A2	MPR
Case 1	18.33	14.10	10.66	0.57	2.42	0.57	2.40	2.68	23.07%
Case 2	18.66	12.80	6.33	0.57	4.15	0.57	1.97	2.25	31.40%
Case 3	11	6.10	3.66	0.81	2.60	0.57	2.54	2.95	44.54%
Case 4	17.75	14.90	8.66	0.5	3.75	0.57	1.06	1.42	16.05%
Case 5	8.60	8.20	4.66	0.54	2.74	0.57	0.20	0.59	4.65%
Case 6	15.20	10.40	5.33	0.83	3.77	0.57	1.75	2.08	31.57%

Abbreviations: A1, baseline phase; B, treatment phase; A2, follow-up; SD, standard deviation; MPR, mean percentage reduction.

Table 2. Mean and Standard Deviation of Reading Time at Baseline, Treatment, 1-Week, 1-Month, and 2-Month Follow-Up Assessments

	MeanA1	MeanB	MeanA2	SDA1	SDB	SDA2	Cohen *d*, A1-B	Cohen *d* A1-A2	MPR
Case 1	524	279.20	144.66	4.58	131.08	12.85	2.63	3.04	46.71%
Case 2	656.33	397.50	303.33	5.50	140.86	23.86	2.59	3.06	39.43%
Case 3	217.75	178	151.66	4.34	24.42	1.52	2.26	2.64	18.25%
Case 4	506	307.60	293.66	4.96	89.35	32.71	3.13	3.61	39.20%
Case 5	433	326.70	264.33	2.54	73.94	5.03	2.03	2.44	24.54%
Case 6	260.80	235	187.66	1.64	30.49	8.32	1.19	1.53	9.89%

Abbreviations: A1, baseline phase; B, treatment phase; A2, follow-up; SD, standard deviation; MPR, mean percentage Reduction.

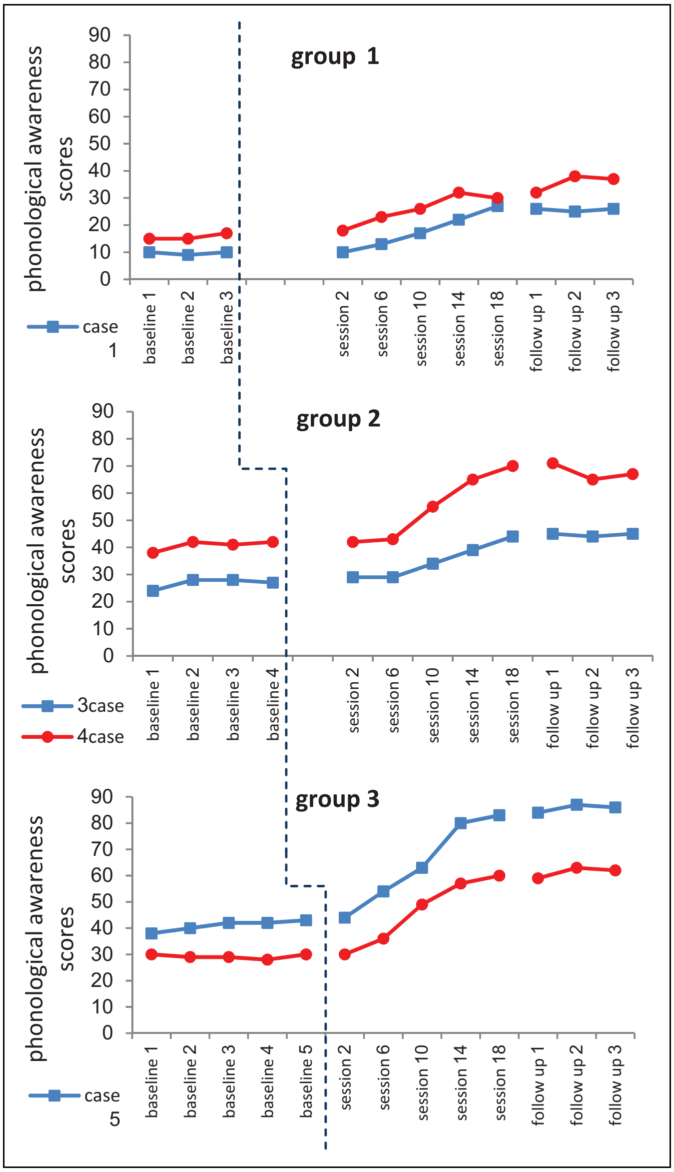

Figure 2. Phonological awareness scores across baseline, treatment, 1-week, 1-month, and 2-month follow-up assessments conducted for all 3 groups.

and reading fluency after NFT. Breteler et al[29,30] have studied the effect of neurofeedback for dyslexia and found small improvements in spelling ability (Cohen $d = 0.26$) but no improvements in reading ability. They also reported the time factor to be a main effect in reading and spelling variables. Moreover, Walker and Norman[35] reported the efficacy of NFT by normalization of targeted EEG abnormalities in dyslexia, with improvements in the reading ability at least 2 grade levels post-NFT.

To explore links between behavioral changes and EEG changes in our participants, EEG power and coherence were analyzed. As predicted, the analysis showed no important change in power of the targeted bands (delta, theta, and beta) after NFT. However, coherence analysis showed interesting changes after the intervention. Interhemispheric coherence normalization in theta at T3-T4 was observed. All participants had higher than normal interhemispheric coherence in the baseline in this band. In addition, we found normalization of coherence of the delta band between Cz-Fz with a lower than normal baseline value. A similar pattern was observed in the coherence of the beta band in Cz-Fz, Cz-Pz, and Cz-C4. Participants had lower than normal beta coherence at the baseline.

Weiss and Mueller[16] stated that dyslexia is a heterogeneous syndrome, as are the results of EEG coherence studies. For example, Sklar et al[14] reported higher intrahemispheric coherence, as well as lower interhemispheric coherence, in dyslexia during reading. Similarly, Leisman[36] found lower interhemispheric and higher intrahemispheric coherence in dyslexia. However, Shiota et al[15] showed high values in inter- and intrahemispheric EEG coherence in rest condition in children with dyslexia.

Coherence shows the functional interconnection of two brain sites, therefore, observed hypercoherence of theta band at T3-T4 may be an indication of abnormal symmetric function of the left/right temporal regions in dyslexia. Different studies have reported the involvement of the temporal region (around T3) in dyslexia; Arns et al[11] reported that high delta and theta activities in the frontal and temporal regions are correlated with weakness of reading and phonological awareness in dyslexia. Flynn and Deering[37] also found an increase in the left temporal theta activity during reading and spelling tasks in dyslexia. Furthermore, structural brain studies have reported decreased gray matter density in the temporal lobe (around T3).[6] In an MRI study by Larsen,[5] the symmetry of planum temporal of right and left homologous regions was found in dyslexia.

Table 3. Mean and Standard Deviation of Phonological Awareness Scores at Baseline, Treatment, 1-Week, 1-Month, and 2-Month Follow-Up Assessments

	MeanA1	MeanB	MeanA2	SDA1	SDB	SDA2	Cohen *d*, A1-B	Cohen *d*, A1-A2	MPI
Case 1	9.66	17.80	25.66	0.57	6.83	0.57	1.67	2.37	45.73%
Case 2	15.66	25.80	35.66	1.15	5.58	3.21	2.51	2.82	39.30%
Case 3	26.75	35	44.66	1.89	6.51	0.57	1.72	2.30	23.57%
Case 4	40.75	55	67.66	1.89	12.62	3.05	1.57	2.27	25.90%
Case 5	41	64.80	85.66	2	16.69	1.52	2	2.67	36.72%
Case 6	29.20	46.40	61.33	0.83	13.04	2.08	1.86	2.55	37.06%

Abbreviations: A1, baseline phase; B, treatment phase; A2, follow-up; SD, standard deviation; MPI, mean percentage improvement.

Table 4. *Z* Scores FFT Coherence for Pre- and Posttreatment

	Delta (1-4 Hz)		Theta (4-8 Hz)		Beta (12-25 Hz)					
	Fz-Cz pre	Fz-Cz post	T3-T4 Pre	T3-T4 Post	Fz-Cz pre	Fz-Cz Post	Cz-Pz pre	Cz-Pz Post	Cz-C4 Pre	Cz-C4 Post
Case 1	−2.33	0.98	2.38	1.12	−3.94	0.49	−2.69	−0.2	−2.55	0.98
Case 2	−3.40	−1.89	2.41	−0.80	−4.94	−1.76	−3.6	0	−4.16	−1.13
Case 3	−2.95	−0.14	2.85	−0.16	−3.89	−0.82	−3.06	−0.99	−3.28	−0.1
Case 4	−3.68	0.77	3.11	−0.63	−7.17	0.94	−3.69	0.25	−3.72	0.01
Case 5	−4.13	−0.62	1.01	−0.38	−6.28	−2.33	−2.78	−0.38	−4.97	−1.86
Case 6	−1.77	0.75	2.06	0.62	−3.62	−0.47	−2.57	−0.05	−2.29	0.1
Mean	−3.043	−0.025	2.303	−0.038	−4.973	−0.658	−3.065	−0.228	−3.495	−0.333

Some evidence has been proposed regarding the neuroplastic changes resulting from neurofeedback and behavioral interventions in clinical populations. For example, Beauregard and Levesque[38] studied the neural bases of NFT effects on selective attention and response inhibition in children with ADHD by functional MRI (fMRI). They suggested that NFT has the capacity to functionally normalize brain systems, mediating selective attention and response inhibition in ADHD children. Furthermore, in a fMRI study,[39] behavioral remediation resulted in the normalization of function in the temporoparietal cortex and inferior frontal gyrus in dyslexia. They suggested "... a partial remediation of language-processing deficits, resulting in improved reading, ameliorates disrupted function in brain regions associated with phonological processing and produces additional compensatory activation in other brain regions."

Moreover, some studies have pointed to sensorimotor deficits in addition to the phonological and reading difficulties in dyslexia. For instance, Abdeldayem and Selim[40] drew attention to sensorimotor and age-related differences between dyslexic and normal children. They suggested a delayed cerebral dyslexic maturation in the children with dyslexia. Thatcher et al[41] explored EEG coherence and phase development from age 2 months to 16.67 years in anterior–posterior and posterior–anterior direction. They found an increase of coherence with age in near electrodes and a decrease of phase in distant electrodes as an indication of brain maturity. This study suggests that the normalization (increase) of beta and delta coherence in Cz-Fz, Cz-Pz, and Cz-C4 (in rest condition) is a sign of integration between sensory and motor areas in the brain of the participants after NFT.

Conclusion

There is converging literature on the capacity of NFT to modulate neural differences in neurodevelopmental disorders in children, including dyslexia. This study showed neurophysiological changes and concurrent improvements in the reading ability and phonological awareness in children with dyslexia post-NFT. The results showed positive changes in the temporal lobes, along with improved coherence between central–frontal and central–parietal areas. This indicates sensory–motor integration and more cerebral maturity in children with dyslexia. However, further research on the cerebral maturity of participants with dyslexia and the application of NFT to target cerebral maturity is needed. Also, the small numbers of cases require cautious interpretation, and additional replication with larger samples would be advantageous.

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Declaration of Conflicting Interests

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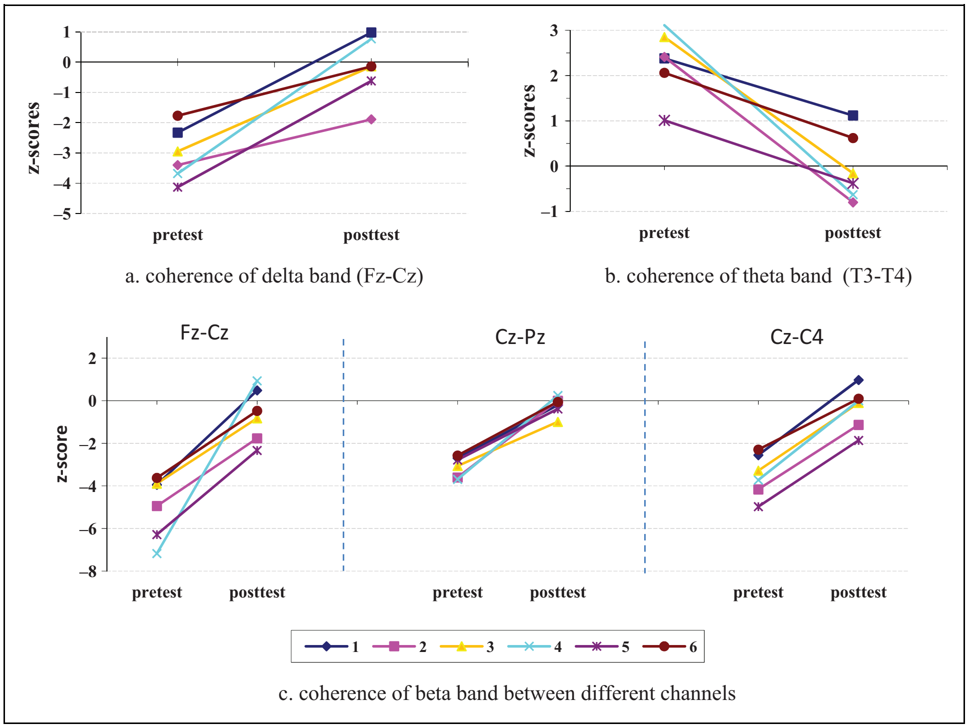

Figure 3. Pattern of *Z* scored coherence changes after neurofeedback training (NFT). A, Coherence of delta band (Fz-Cz). B, Coherence of theta band (T3-T4). C, Coherence of beta band between different channels.

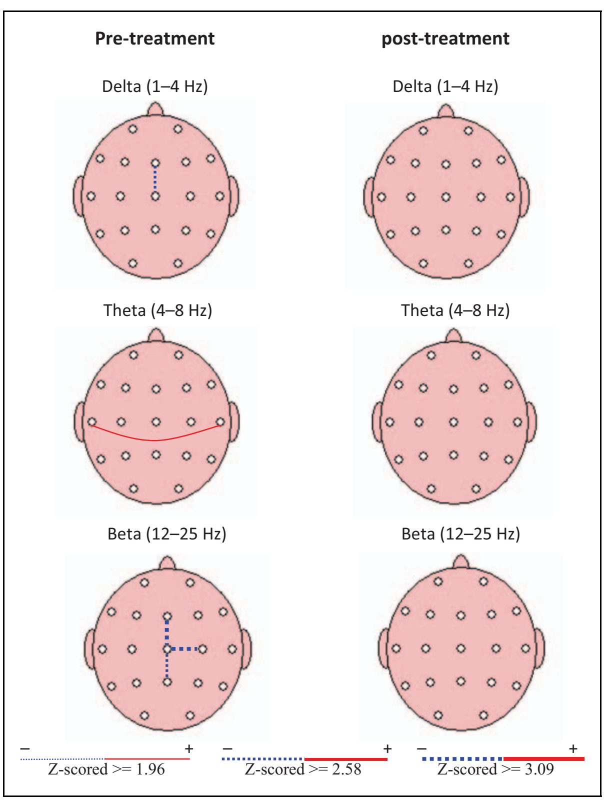

Figure 4. Diagrammatic illustration of averaged Z scored coherence in delta, theta, and beta bands for pre- (left) and posttreatment (right). The solid line indicates the hypercoherence and square dot lines indicate the hypocoherence.

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