# Does it help to train attention in dyslexic children: Pilot case studies with a ten-session neurofeedback program

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# Does it help to train attention in dyslexic children: pilot case studies with a ten-session neurofeedback program

**Abstract:** Neurofeedback is a biofeedback training of electroencephalogram (EEG) activity through operant conditioning where an individual is trained to increase or inhibit the brain activity in specific frequency ranges. Studies have demonstrated its efficacy to reduce inattention, impulsivity and hyperactivity in children with attention deficit hyperactivity disorder (ADHD), with the mostly used training protocols on modulation of θ/β ratio. Given the comorbidity and common cognitive deficits between ADHD and developmental dyslexia, this study aimed to explore the effects of θ/β neurofeedback on cognitive deficits in Chinese dyslexic children. In the present case study, a multiple-baseline design was adopted, and the effects of training were investigated from both neurophysiological and neuropsychological levels. Four dyslexic children completed 10 weekly sessions of θ suppression and β enhancement neurofeedback training in the sensorimotor cortex. Pre- and post-assessments consisted of neurophysiological measures, neuropsychological assessments, and parental reports. Neurofeedback training reduced θ/β ratios in all participants. All participants also improved in measures of auditory vigilance and phonological awareness.

**Keywords:** attention training; dyslexia; neurofeedback.

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## Introduction

### Prevalence and characteristics of dyslexia in Chinese children

Developmental dyslexia is a neurobiological disorder characterized by a severe impairment in reading skills acquisition that affects approximately 5%–17% of school-aged children at different degrees worldwide [1]. Dyslexia refers to compromised reading ability falling substantially below the norms, interfering with academic achievement or everyday activities that require reading skills [2]. The prevalence rate of dyslexia in Chinese children in Hong Kong is 12.6%, with a boy/girl ratio of 1.6:1 [3]. Consistent with the comorbidity statistics in non-Chinese populations [4], 26% of Chinese children with dyslexia also had attention deficit hyperactivity disorder (ADHD), and 35% of Chinese children with ADHD also met the criteria for dyslexia (the corresponding rate was 10%–30% in non-Chinese populations).

### Multidimensional neuropsychological deficits in dyslexia

#### Visual attention

Reading acquisition, also termed phonological decoding, is an attention demanding process. Several lines of evidence indicated that visual attentional difficulties are correlated with dyslexia. First, poorer performance on visual search tasks has been found in dyslexic groups, which could result either from a perceptive grouping dysfunction or an attention shift problem. Second, people with dyslexia have difficulties maintaining and focusing attention. They distribute attentional resources more diffusely but once their attention is engaged it cannot be easily disengaged [5]. Therefore, they have prolonged attentional dwell time and lack of attentional control at the left hemisphere during the encoding of words [6]. Third, dyslexic children show defective spatial orientation of visual attention and have difficulties orienting attention on spatial cueing tasks [7]. More specifically, they demonstrate an asymmetric distribution of attentional resources across the visual field, as shown by mild left inattention in cue-target reaction tasks and abnormally high sensitivity in the right visual field. Fourth, attention shift problems are noted in dyslexic children where they show poorer control in shifting attention between channels, suggesting an attentional control dysfunction [8].

### Phonological awareness

Phonological deficit is widely regarded as the cognitive basis of dyslexia [9]. Phonological awareness involves selective attention to the phonological features within spoken words, which is directly related to difficulties in reading acquisition [10]. In Cantonese, attention is also needed in rote memorization and drilling of graphic-sound association between sound and shape of Chinese characters. However, a recent study implicated that only 18.3% of dyslexic children solely exhibited a phonological deficit, whereas the majority (76.6%) showed multiple deficits as well. Such heterogeneity of multiple deficit manifestation also appears evident in the Chinese population that over half (57%) of the sample had a triple or quadruple cognitive deficits [11].

### Inhibitory control

Response inhibition which plays a central role in the reading process was suggested to be particularly relevant to dyslexia [12]. Response inhibition refers to the 'ability to deliberately inhibit dominant, automatic, or prepotent responses when necessary' [13]. One of the premier paradigms for assessing inhibition is the stop signal task [14], which has been used in several double dissociation studies investigating the overlap and specificity of cognitive deficits in dyslexia and co-occurring ADHD. Significantly slower inhibitory processes were found in dyslexic children compared with age-matched control subjects.

## Neuropathophysiological basis underlies neuropsychological deficits in dyslexia

Anatomical studies on dyslexic readers of alphabetical languages showed an absence of the usual left-right hemisphere asymmetry of the planum temporale, suggesting a role of the left inferior frontal gyrus in speech perception, rapid auditory processing, and phonological aspects of reading. According to electroencephalogram (EEG) studies on alphabetical languages, the core dysfunctions in dyslexia consisted of increased activity of slow frequency bands (δ and θ) at left frontal and right temporal regions, bilateral increased coherence of slower frequency bands (δ and θ), as opposed to acquired-compensatory mechanisms consisting of right-hemispheric increased coherences in the higher frequency bands (α and β), and a left frontal increased coherence of slower frequency (δ and θ) bands originating from C3 and FC3 [15].

## Neurofeedback training for dyslexia

Over the past few decades, comprehensive studies on the neurophysiological basis of developmental dyslexia have fostered the development of neurofeedback or EEG biofeedback training. With the use of operant conditioning, desirable brain activity is rewarded and undesirable brain activity is inhibited. Through neurofeedback, individuals learn self-regulating bioelectrical brain processes, as assessed by EEG. Electrodes are attached to the scalp and specific parameters such as α rhythm, sensorimotor rhythm (SMR), or θ/β ratio are extracted in real time. Easily understandable displays are presented to the participants. Whenever the brainwaves find their way to meet the preset training parameters, the participant is quickly rewarded with positive feedback. Neurofeedback training is believed to help elicit growth and changes at cellular levels of the brain, which in turn support brain functioning and behavioral cognitive performance [16].

Neurofeedback treatment for ADHD has been suggested to be 'efficacious and specific' (level 5) with a large effect size for inattention and impulsivity, and medium effect size for hyperactivity [17]. The scope of neurofeedback training has been expanded to children with attention deficit disorder (ADD) and learning disability (LD). In Lubar's EEG biofeedback protocol, children were taught to increase β and SMR frequencies while concurrently decreasing their abnormally high θ frequencies, along with academic training on reading, arithmetic, and spatial tasks [18]. This early study indicated that neurofeedback normalized physiological indicators of low arousal and brainwave patterns, and improved achievement performance, providing initial rationale and basic methodology for exploring neurofeedback training as a potential treatment modality for ADD and LD children. Lubar further concluded that neurofeedback training can help dyslexic children decrease θ (4–8 Hz) and increase β (14–20 Hz) activity, as well as providing remediation for children with LD [18]. Over the years, studies on θ suppression and β enhancement demonstrated positive effects in children with ADD and LD including enhanced attention and visual-motor integration, increased IQ scores, and significant reduced inattentive behavior [19]. Apart from attention enhancement, neurofeedback training of enhancing SMR (12–15 Hz) and reducing θ (4–8 Hz) at either C3 or C4 was shown to be effective in changing hemispheric visual word recognition [20]. In short, neurofeedback training using classic training protocol (θ suppression/β enhancement at C3/C4) repeatedly demonstrated effectiveness on treating attention deficits and reading problems. These findings supported the postulation of symptoms of ADHD and dyslexia as multiple manifestations of the same neurological dysfunction. Given the high comorbidity between ADHD and developmental dyslexia, as well as their shared cognitive deficits, it gives rise to the speculation that the treatment efficacy on ADHD could be replicated in the dyslexic population.

Based on the empirical evidence above, neurofeedback training in the present study adopted the most widely used protocol of θ suppression/β enhancement training at the sensorimotor cortex (C3 and C4 regions in accordance to the 10–20 system) [21]. The role of the sensorimotor cortex is particularly relevant in Chinese language acquisition. The extensive writing exercise during Chinese reading acquisition has been suggested to shape the cortical center in the posterior portion of the left middle frontal gyrus (LMFG), anterior to the sensorimotor cortex that governs motor functions. Besides, enhancement of attention was suggested to be associated with improved spelling in dyslexic children after neurofeedback training [22]. Taken together, we believe that Chinese dyslexic children could benefit from θ suppression/β enhancement training at the sensorimotor cortex. Two types of protocols were adopted in this study, namely, the power and bipolar protocols. The function of the power protocol is to address the modular insufficiencies or excesses in the brain region, whereas that of the bipolar protocol is to normalize interhemispheric incoherence.

The power protocol was adopted to increase β and reduce θ at the C3 region, which aimed to alleviate the dyslexic children's inattentive symptoms. Dysfunctional higher frequency β (termed hi-β at 21–30 Hz) associated with anxiety and hyperalertness was down-trained. Increased activation of the central area (C3 and C4) is associated with improvement of successful learning and reading prerequisite such as improved visual attention, perceptual/attentional readiness, logical deduction and reasoning, and functional synthesis of past experience and memory [21]. The bipolar protocol was also adopted to address brain dysfunctional connectivity, which is commonly found in dyslexic populations [23]. Studies showed improved spelling, attention switching, and response inhibition in dyslexic children after neurofeedback training of integrated power and bipolar protocols [22]. In light of dysfunction in attention deficit, perceptual-motor processing and functional asymmetries between hemispheres, and optimizing functional connectivity between bilateral cortices governing attention and motor functioning (i.e., C3, C4) could also benefit Chinese dyslexic children through the enhancement of sensorimotor integration.

The present study was an exploratory case study aimed to investigate whether neurofeedback could benefit the dyslexia-related neuropsychological deficit in Chinese dyslexic children. In view of the high attrition rate in normal neurofeedback training that involves 30–40 sessions, this study aimed to explore whether a shorter term program would already lead to some observable changes to serve as an incentive for continued training. In the present pilot study, we explored the feasibility and the clinical implication of neurofeedback training as an intervention to improve attention and inhibitory control in Chinese dyslexic children. The θ suppression and β enhancement approach at the sensorimotor cortex (C3 and C4) was adopted, using both power and bipolar training protocols. The hypotheses of this study are:

- Neurofeedback training will lead to changes in brainwave activity as reflected in θ/β ratios.
- Neurofeedback training will improve neuropsychological deficits of attention and inhibitory control in Chinese dyslexic children.

# Methods

## Study design and procedures

A multiple-baseline, single-case study design was adopted, which aimed to investigate the children's θ/β brainwaves amplitude ratios and their performance on neuropsychological tasks related to attention and inhibitory control before and after training. Varying time schedules were used to examine the true impact of neurofeedback training on outcome measures. A telephone interview was conducted with parents before training to survey developmental history and any current problems of the participants. Pre- and post-assessments consisted of neuropsychological functioning, including sustained attention, selective attention, attentional switching, vigilance, and inhibitory control. Participants' intellectual functioning was reconfirmed by the Wechsler Intelligence Scale for Children – Fourth Edition (Hong Kong) [WISC-IV (HK)]. All assessments were performed by two clinical psychology trainees. Pre- and post-assessments each took around 2 h for a single participant. Baseline measurement of brainwaves began 1 week after pre-assessment, conducted in single-blind placebo neurofeedback sessions, where the children's brainwaves were recorded but rewards in the game were given randomly. The training phase consisted of ten neurofeedback training sessions for each participant, with a mix of power protocols (C3/β) and bipolar protocols (C3–C4/β), targeted to increase β amplitude and decrease θ and hi-β amplitudes at the primary sensorimotor cortex (i.e., C3 and C4). The amplitude levels of these brainwave frequencies, namely θ, β, and hi-β, were monitored and recorded in each training session. The θ/β ratios were analyzed and compared as dependent outcome measures of neurofeedback training. Within-subject comparisons of pre- and post-cognitive correlates and cognitive outcome measures were also conducted. The study has been approved by the Institutional Review Board (Ethics Committee) of the Chinese University of Hong Kong.

## Measures

### Wechsler Intelligence Scale for Children – Fourth Edition (Hong Kong)

[WISC-IV (HK)] Intelligence was evaluated using the WISC-IV (HK) [24] short form, to rule out gross intellectual deficit in the participants. A local-based norm was used to convert raw scores into full-scale IQ estimates.

### Test of Everyday Attention for Children (TEA-Ch)

The TEA-Ch [25] is an assessment tool for attention comprising nine subtests. Test battery is built upon a three-factor model consisting of sustained attention, selective attention, and higher level 'executive' control. Four subtests were used in the present study, namely, Code Transmission, Sky Search, Opposite World, and Creature Counting.

### CPT Vigilance Task

The auditory CPT (CPT-AX) [26] was adopted. The AX version of the CPT has letters A, B, C, D, E, F, G, H, M, and X. The ten English alphabets were digitally recorded with a female voice. All participants listened to the letter sequence through an earphone. They were asked to respond by pressing the space bar on the keyboard when identifying letter sequences of AX. A 240-letter sequence with 48 AXs was presented. The time on task was approximately 960 s (approx. 16 min). Stimulus duration was 350 ms.

### Stop-IT

Computerized shape judgment task software STOP-IT [27] was used to measure motor impulsivity. The experiment consisted of 32 practice trials and three blocks of 64 trials each where participants were required to discriminate between a square and a circle. The fixation sign (+) and stimuli were presented in the center of the screen, in white, on a black background. On no-signal trials, only the primary task stimulus is presented, and participants were instructed to respond to the stimulus as fast and as accurately as possible. On stop-signal trials, the primary task stimulus is followed by an auditory stop signal and participants were instructed to withhold their responses. The stimulus remained on the screen until participants responded, or until 1250 ms (i.e., the maximum reaction time) had elapsed. The interstimulus interval was 2000 ms, which was independent of reaction time. On the stop-signal trials, a stop signal was presented after a variable stop-signal delay (SSD). SSD was initially set at 250 ms and was adjusted continuously with the staircase tracking procedure. Participants had to wait for 10 s between blocks.

### The Hong Kong Test of Specific Learning Difficulties in Reading and Writing (HKT-SpLD) – Phonological Awareness Subtests

The HKT-SpLD [28] was developed to assess developmental dyslexia in primary school children. There are three literacy and nine cognitive subtests in the HKT-SpLD. Two phonological awareness subtests are used to examine the participant's awareness of phonological onsets and rhymes, which were found to be related significantly to Chinese language reading performance [29]. There were 15 trials for the Onset Detection and 18 trials for the Rhyme Detection subtests. In each trial, the participant would hear three Chinese syllables presented by the CD player. The Chinese syllables were names of common objects, and the pictures were shown simultaneously with the audio presentation. The participants were asked to indicate among the three syllables which two sounded familiar (e.g., [sau]1, [fo]1, [fung]1 in Onset Detection, and [gaam]1, [bing]1, [daam]1 in Rhyme Detection).

## Participants

Participants were four children (three boys and one girl) aged between 9 and 12 years, recruited from the Hong Kong Association for Specific Learning Disabilities. According to their psychological reports provided, all participants met the diagnostic criteria for learning disorder not otherwise specified according to the Diagnostic Statistical Manual for Mental Disorders (Fourth Edition, Text Revision) (DSM-IV-TR) [2] and the HKT-SpLD [30], with a full-scale IQ score greater than 70 in the WISC-IV (HK) [24]. All participants did not have a history of brain injury or other neurological disorder, serious medical condition, substance addiction, and family history of a genetic disorder. During the course of training, all participants were not engaging in any additional therapies for their attention and inhibition problems except Case 4, a boy with comorbid ADHD continued his prescription regime on Concerta. For this particular child with comorbid ADHD, we aimed to explore the extra benefit of neurofeedback training on top of first-line medical treatment. Demographic and baseline presentation of the participants are shown in Table 1.

## Neurofeedback training

### Training design

Each participant received ten 45-min neurofeedback training sessions, once per week at the same time of the day at the Department

**Table 1** Characteristics of the participants.

| Participant number | Sex | Age | Grade | Clinical presentation | IQ estimate (WISC-IV-HK) |
|---|---|---|---|---|---|
| Case 1 | Female | 10 years, 11 months | Primary 5 | Dyslexia with slow response and poor articulation | 82–95 |
| Case 2 | Male | 9 years, 6 months | Primary 4 | Dyslexia with inattentive features, weakness in inhibition | 58–71 |
| Case 3 | Male | 9 years, 8 months | Primary 4 | Dyslexia with inattentive and fidgety features, and weakness in fine motor skills | 82–95 |
| Case 4 | Male | 11 years, 4 months | Primary 5 | Dyslexia with ADHD | 80–94 |

of Psychology, The Chinese University of Hong Kong. All training sessions were conducted by two clinical psychology trainees.

## Training protocols

The β enhancement and θ suppression approach was adopted, and began with the C3/β power protocol, followed by the C3–C4/β bipolar protocol (see Table 2). The power protocol was a standard ADHD training protocol, aimed at reducing θ (4–7 Hz) while increasing β (15–20 Hz) at C3 (reference at A1). The bipolar protocol aimed at optimizing interhemispheric functional connectivity and sensorimotor integration between C3 and C4. The signal at location C3 (in the power protocol) and C3–C4 (in the bipolar protocol) was fed back to the participants in the visual form of a computer game.

## Training equipment and setup

A portable Brain Trainer amplifier and recording system, developed and manufactured by Spectrum Learning, Singapore, was used [31]. Skin sites were cleaned with Nuprep Skin Prep gel, and electrodes were connected to the scalp and skin with Ten 20 Conductive Paste. Electrodes were placed on the scalp and earlobes according to the International 10–20 system. Single-channel setup was used for neurofeedback training and concurrent data collection. In the power protocol, an active electrode was attached to the left sensorimotor cortex (C3), with reference to the same side earlobe (A1) and a ground electrode to the contralateral earlobe (A2) (Figure 1). In the bipolar protocol, an active electrode was attached to the left sensorimotor cortex (C3), with reference to the right sensorimotor cortex (C4) and a ground electrode to the left earlobe (A1) (Figure 2). EEG was recorded and the relevant frequency components were extracted and fed back using an audiovisual online feedback loop in the form of a video game.

**Table 2** Outline of power and bipolar protocols used in the training sessions.

| Participant | No. of placebo sessions | Power protocol (C3/θ–β) | Bipolar protocol (C3–C4/θ–β) |
|---|---|---|---|
| Case 1 | 4 | Sessions 1–6 | Sessions 7–10 |
| Case 2 | 3 | Sessions 1–7 | Sessions 8–10 |
| Case 3 | 2 | Sessions 1–6 | Sessions 7–10 |
| Case 4 | 1 | Sessions 1–3 | Sessions 4–10 |

## Training procedures

Training involved monitoring and influencing the θ (4–7 Hz), β (15–20 Hz), and hi-β (22–30 Hz) and were adopted in the Inhibit I, Reward, and Inhibit II bands, respectively. Each child was administered the 'Bugz Raider' game using the β training protocol. The participants' task was to help the fish produce bubbles for killing bugs.

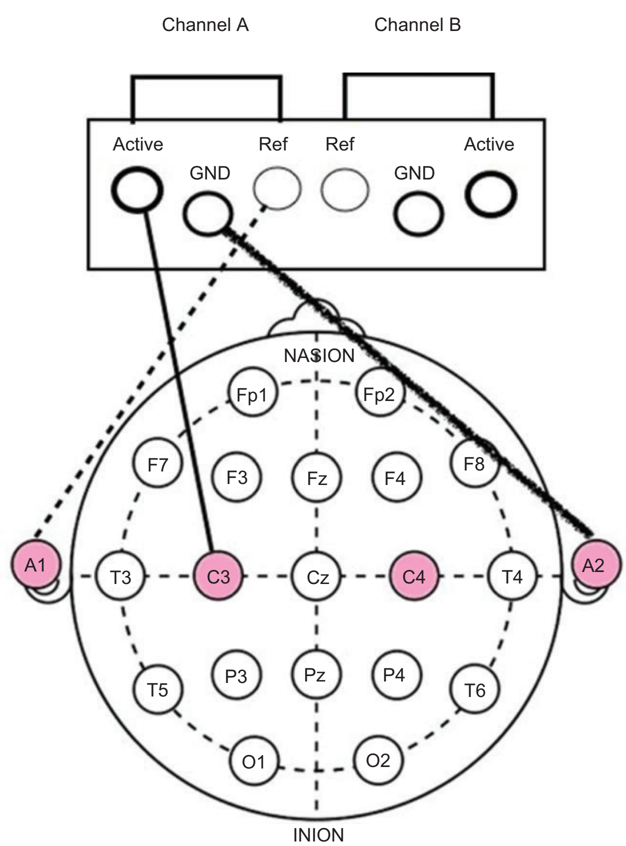


**Figure 1** Set up for the power protocol.

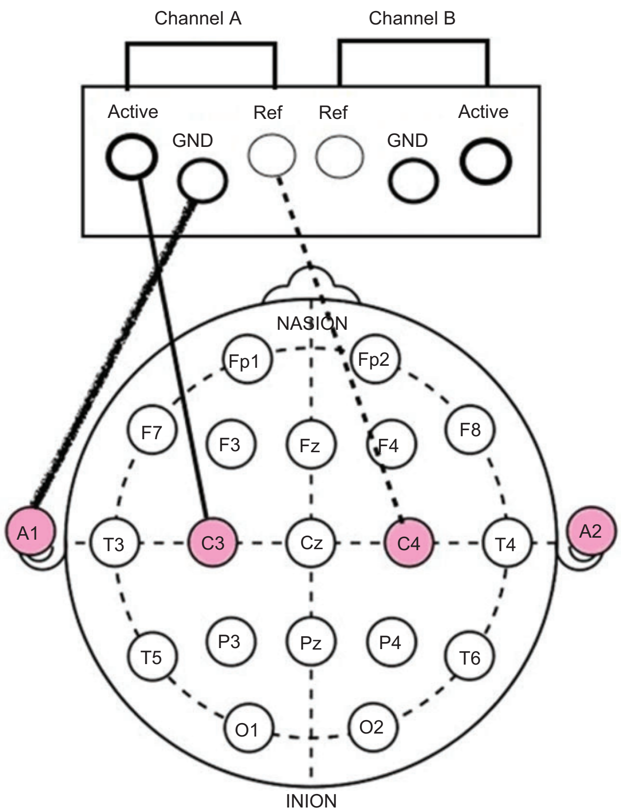


**Figure 2** Set up for the bipolar protocol.

Rewards were given when the amplitude of θ waves and hi-β wave activity was inhibited below the threshold, and β wave activity produced was above the threshold. To create bubbles for the fish and shoot the bugs, participants had to produce brainwaves that fit the above criteria. The thresholds set for reward and inhibit bands were individualized for each subject according to their clinical presentations. The game had ten trials with a 10-s break at the intervals showing the scores. Participants were simply told to concentrate, inhibit motor actions (i.e., fidgeting), and explore appropriate ways of controlling their fish with no explicit instructions. Parents were required to fill out an observation form to provide feedback on the cognitive, behavioral, and affective changes of their children within 12 and 48 h after each training session.

# Results

## Pre-treatment dyslexia profiles of participants

Pre-treatment dyslexia profiles of the four participants are summarized as follows. Case 1 was a girl aged 10 years and 11 months with average IQ, slow response, and poor articulation; and average attentional performance in TEA-Ch. Case 2 was a boy aged 9 years and 6 months with low IQ, inattention, and poor inhibitory control; and deficit attentional performance in TEA-Ch. Case 3 was a boy aged 9 years and 8 months with poor fine motor skills, inattention, and fidgeting; and deficit attentional performance in TEA-Ch. Case 4 was a boy aged 11 years and 4 months with comorbid ADHD, slow response, and poor articulation; and deficit attentional performance in TEA-Ch. According to their baseline performance in TEA-Ch, all participants except Case 1 had impaired attention in terms of sustained attention, selective attention, and/or attention shift. The complexity of dyslexia was reflected in the heterogeneity in our small sample that Case 2 was within borderline IQ, and Case 4 had comorbid ADHD. Nevertheless, the heterogeneous sample had provided the study with additional information for the understanding of the effect of neurofeedback on pure dyslexia, dyslexia comorbid with low IQ, and dyslexia comorbid with ADHD.

## Pre- and post-treatment changes in neurophysiological measures

Brainwave data collected throughout the training was divided into three sections, namely, the placebo sessions, power training, and bipolar training. A downward trend of the θ/β ratio was noted in all participants after ten training sessions, with a greater decrease in participants with pure dyslexia, and a smaller decrease in participants with comorbidity. Case 1 showed the largest reduction amplitude of the mean θ/β ratio by 46.80%, followed by Case 3 with a decrease of 25.64%. Case 4, who had dyslexia with comorbid ADHD, showed a θ/β ratio decrease of 16.09%. Case 2, who had dyslexia with comorbid low IQ, showed a θ/β ratio decrease of 14.31%. In short, all participants showed evidence of neurofeedback training as indexed by decreased θ/β ratios over time (see Table 3).

**Table 3** Percentage changes of θ/β ratios after neurofeedback training.

| Mean θ/β ratio | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|
| Baseline (placebo sessions) | 1.62 | 1.55 | 1.91 | 1.19 |
| Power training | 1.26 | 1.84 | 2.07 | 1.28 |
| Bipolar training | 0.87 | 1.35 | 1.55 | 1.05 |
| Session 10 | 0.86 | 1.33 | 1.42 | 1.00 |
| % Change (baseline vs. session 10) | −46.80% | −14.31% | −25.64% | −16.09% |

### Pre- and post-treatment changes in neuropsychological measures

All participants demonstrated remarkable improvement on reaction time and error commissions, and phonological awareness. Among these, the most prominent neuropsychological improvements were noted in vigilance and phonological awareness. All participants showed improvement in the auditory vigilance task (i.e., CPT-AX), as reflected by the substantial reduction in reaction times, and omission and commission errors. Moreover, all participants showed progress in phonological awareness, where Case 2 and Case 3 demonstrated clinically significant changes. Improvement on inhibitory control was noted in most participants. Enhancement in attention was also demonstrated in various degrees and in different aspects including basic attention, sustained attention, selective attention, and attentional switching (see Table 4).

## Discussion

To the best of our knowledge, this is the first pilot study exploring the effects of neurofeedback training on neuropsychological deficits in Chinese children with developmental dyslexia. The training regime involving θ suppression/β enhancement at the sensorimotor cortex was originally developed for ADD and developmental dyslexia. Evaluation of the present study will be discussed in terms of neurophysiological and neuropsychological changes. Future directions of neurofeedback research on dyslexia will be discussed. Consistent with previous neurofeedback studies on children with dyslexia and ADD, the present neurofeedback training successfully reduced θ waves and increased β waves in all participants, as reflected by the decreasing θ/β ratios. The consistent suppression of θ frequencies and enhancement of β activation over time across sessions were in line with the conceptualization of β training as an enhancement in a nonadrenergic vigilance network and fast response tendencies, as reflected by the participants' remarkable improvement on reaction time and error commissions, which indicated a heightening of alertness and attentiveness. Given that the present study had only ten training sessions, which is approximately one-third of a standard neurofeedback training protocol, our results demonstrate the potential effectiveness of θ suppression/β enhancement training at C3/C4 on various attention deficits in children with dyslexia.

After the neurofeedback training, all participants experienced prominent improvement in basic attention (i.e., vigilance) in which some of them even showed better performance in higher attentional control (i.e., sustained attention, selective attention, and attentional switching). The implication of the current findings is twofold. On the one hand, participants' baseline presentation supported our presumption of attention deficits in dyslexia as implicated in various lines of research. On the other hand, the preliminary improvement in attention yielded after the training supported our postulation that the efficacy of neurofeedback training on ADHD may extend to the dyslexic population, which is consistent with previous research findings.

Apart from visual and auditory attention, our results revealed that θ suppression/β enhancement training at the sensorimotor cortex (C3, C4) also produces some improvement in participants' efficiency of inhibitory control (except Case 3). The underlying mechanism is not known at present, but we speculate that improvement may be mediated by two factors. First, improved reaction time caused by β enhancement may also benefit the reaction time eliciting response inhibition. Second, training at the sensorimotor cortex may generate enhancement of motor skills. Indeed, the STOP-IT task measures behavioral inhibition or executive-motor inhibition in which motor speed, attentional processes, and higher cognitive processing are involved. Thereby, β enhancement training at the sensorimotor cortex may remediate a deficit in behavioral inhibitory control that is commonly found in dyslexic children.

Enhancement in phonological awareness in all participants implicated that neurofeedback at C3 may be associated with heightened awareness of phonological components in Chinese dyslexic children. Possible explanations may point to the role of the left secondary motor area (C3) in mediating information between Broca's area (left frontal) and Wernicke's area (left temporal) during phonological segmentation, or that C3 is of close proximity to the LMFG involved in Chinese phoneme processing.

The connection between improved motor skill performance and phonological awareness may be explained by the cerebellar theory [32, 33] that general motor skills would affect writing and speech articulation, which would affect the acquisition of internal representations of speech in terms of phonological awareness. However, the notion that phonological deficit is caused by motor impairment has not been widely supported [34]. Although motor impairment is prevalent among dyslexic children, a causality relationship between motor skill and phonological awareness has yet to be established.

**Table 4** Results on neuropsychological measures on attention and inhibitory control, and phonological awareness.[a]

| | Case 1 (Girl, 10 years and 11 months) | | | Case 2 (Boy, 9 years and 6 months) | | | Case 3 (Boy, 9 years and 8 months) | | | Case 4 (Boy, 11 years and 4 months) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pre | Post | Diff. | Pre | Post | Diff. | Pre | Post | Diff. | Pre | Post | Diff. |
| CPT-AX | | | | | | | | | | | | |
| RT mean (s.d.) | 696.26 | 638.13 | −8.35% | 1240.72 | 959.28 | −22.68% | 940.30 | 769.76 | −18.14% | 862.80 | 811.38 | −5.96% |
| | (146.03) | (18.57) | (−87.3%) | (830.54) | (230.91) | (−72.2%) | (989.53) | (59.73) | (−94.0%) | (435.85) | (907.39) | (+8.2%) |
| Hit, % | 100.00 | 97.00 | −3.0% | 69.00 | 83.00 | +14.0% | 39.00 | 53.00 | +14.0% | 61.00 | 71.00 | +10.0% |
| CE | 0 | 1 | +1 | 14 | 8 | −6 | 31 | 14 | −17 | 23 | 18 | −5 |
| OE | 11 | 3 | −8 | 16 | 8 | −8 | 28 | 31 | +3 | 12 | 3 | −9 |
| TE | 11 | 4 | −7 | 30 | 16 | −14 | 59 | 45 | −14 | 35 | 21 | −14 |
| Stop-signal | | | | | | | | | | | | |
| SSRT | 325.9 | 176.2 | −45.93% | 678.6 | 540.1 | −20.41% | 227.5 | 272.0 | +19.56% | 376.8 | 307.6 | −18.37% |
| p(r/s), % | 39.6 | 48.9 | +9.3% | 69.6 | 61.7 | −7.9% | 47.8 | 45.8 | −2% | 45.7 | 46.8 | +1.1% |
| p(i/s), % | 60.4 | 51.1 | −9.3% | 30.4 | 38.3 | −7.9% | 52.2 | 54.2 | +2.0% | 54.3 | 53.2 | −1.1% |
| IF | 0.19 | 0.29 | +52.63% | 0.04 | 0.07 | +75.00% | 0.21 | 0.20 | −4.76% | 0.14 | 0.17 | +21.43% |
| NSRT | 723.9 | 740.0 | +2.35% | 820.9 | 682.7 | −16.8% | 843.4 | 833.0 | −1.23% | 749.3 | 693.7 | −7.4% |
| p(r/ns), % | 98.6 | 100.0 | +1.42% | 62.2 | 81.0 | +30.2% | 84.6 | 92.9 | +9.8% | 93.7 | 95.1 | +1.5% |
| TEA-Ch[b] | | | | | | | | | | | | |
| Code-acc | 14 | 12 | −2 | 4 | 4 | 0 | 5 | 10 | +5[c] | 3 | 3 | 0 |
| Sky-time | 8 | 6 | −2[c] | 1 | 1 | 0 | 9 | 11 | +2 | 10 | 11 | +1 |
| Sky-attn | 7 | 6 | −1 | 1 | 1 | 0 | 8 | 10 | +2 | 8 | 10 | +2[c] |
| Oppo[s]-time | 5 | 7 | +2 | 1 | 2 | +1 | 3 | 9 | +6[c] | 7 | 9 | +2 |
| Oppo[o]-time | 8 | 9 | +1 | 1 | 1 | 0 | 7 | 11 | +4 | 8 | 11 | +3 |
| CC-acc | 14 | 12 | −2 | N/A[d] | N/A[d] | N/A[d] | 12 | 10 | −2 | 6 | 9 | +3 |
| CC-time | 8 | 11 | +3 | N/A[d] | N/A[d] | N/A[d] | 7 | 9 | +2 | 3 | 6 | +3 |
| Phonological awareness | | | | | | | | | | | | |
| Onset detection | 9 | 13 | +4 | 5 | 12 | +7[c] | 7 | 12 | +5[c] | 11 | 13 | +2 |
| Rhyme detection | 10 | 12 | +2 | 10 | 13 | +3 | 11 | 11 | 0 | 10 | 11 | +1 |

[a]Diff., difference; Post – Pre/Pre×100% or Pre (scaled score) – Post (scaled score); +, increase; –, decrease; CE, commission error; OE, omission error; TE, total error; SSRT, mean stop signal reaction time; NSRT, mean no-signal (i.e., go-signal) reaction time; p(r/s), probability of responding stop-signal trial; p(i/s), probability of inhibiting stop-signal trial; p(r/ns), probability of responding go-signal; IF, inhibition function: efficiency of the inhibitory mechanism controlling for differences in mean go-signal reaction time; Code-acc, total number of digits correctly reported (accuracy); Sky-time, time-per-target score; Sky-attn, subtraction of the 'motor control'; Oppo[s]-time, time taken for completion in same world condition; Oppo[o]-time, time taken for completion in opposite world condition; CC-acc, accuracy; CC-time, time taken for completion; [b]scaled scores; [c]significant change; [d]Case 2 failed to comprehend instruction for the Creature Counting subtest.

In addition to the overall patterns presented above, the effects of neurofeedback training seems to be subject to the participants' individual profiles. For example, Case 1, who had no apparent attention problem to begin with, showed less improvement in attention as compared with Case 3 and Case 4 who had marked baseline inattentive and hyperactive features. Moreover, participants' IQ may also affect the effectiveness of neurofeedback training. For example, Case 2, who presented with low IQ, showed less improvement in attention and inhibitory control, and a relatively less θ/β ratio reduction than his normal IQ counterparts. A possible explanation for these findings is that because neurofeedback training is based on the principle of operant learning, its therapeutic effect might be impeded in individuals who have limited intelligence for learning. Taken together, the effect of neurofeedback is more prominent in dyslexic individuals who show obvious attention deficiency, such as individuals with dyslexia comorbid with ADHD. Besides, intelligence can also affect the efficacy of neurofeedback training in which individuals with dyslexia comorbid with low IQ may be less sensitive to neurofeedback conditioning.

In conclusion, both neurophysiological and neuropsychological changes were observed in the four participants who had undergone the ten-session neurofeedback program. Results obtained from this pilot study suggest that a more elaborate study is warranted with more participants, more training sessions over a longer period, and a control group. However, caution should be taken in bipolar training to maintain a dynamic range of functional connectivity, yet preventing the occurrence of convulsive seizure during extra high coherence states. Future studies involving quantitative EEG will also be needed to explore the underlying mechanism of observed changes.

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