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The Effect of Binaural Beats on Reading Fluency and Phase Lag Value in Dyslexic Children

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Abstract

Objective: This study investigated the effects of beta- and theta-frequency binaural beats on reading fluency and cortical connectivity, measured via phase lag value (PLV), in children with dyslexia.

Methods: Fifty dyslexic children (aged 7.5–8.3 years) were randomly assigned to receive 12 sessions of beta binaural beats (15 Hz), theta binaural beats (5 Hz), or isochronous tones (control). Reading fluency was assessed using the Nilipour Reading Test at pre-test, post-test, and six-week follow-up. Resting-state EEG was recorded to compute PLV in theta and beta bands.

Results: Results showed significant improvements in reading fluency for the beta group at post-test and follow-up compared to theta and control groups. PLV increases were observed in beta-band fronto-central and left fronto-temporal networks, and theta-band temporo-parietal networks, correlating with enhanced reading performance.

Discussion: These findings suggest that beta binaural beats may enhance phonological processing and executive functions in dyslexia through neural entrainment, offering a non-invasive auditory approach to support reading skills.

Keywords: Binaural Beat, Cortical Connectivity, Dyslexia, Phase Lag Value, Reading Fluency

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1. Introduction

Developmental dyslexia, a neurodevelopmental disorder affecting approximately 5–10% of school-aged children, is characterized by persistent difficulties in accurate and fluent word recognition despite adequate intelligence and educational opportunities (Shaywitz & Shaywitz, 2005). At the neural level, dyslexia often involves atypical functional connectivity in language-related brain networks, particularly in the left hemisphere, where reduced synchronization in theta (4–8 Hz) and beta (13–30 Hz) frequency bands impair phonological processing and reading fluency (Žarić et al., 2017). Studies using electroencephalography (EEG) have consistently shown diminished phase synchronization, as measured by phase lag value (PLV), in temporo-parietal and fronto-temporal regions among dyslexic individuals, reflecting disrupted integration of auditory and visual information essential for reading (Finn et al., 2014; Fraga González et al., 2018).

Binaural beats (BBs), generated by presenting slightly differing pure tones to each ear, induce perceptual illusions that can entrain brain oscillations to the beat frequency, potentially modulating cognitive functions (Oster, 1973). Theta BBs (4–8 Hz) are associated with relaxation and memory consolidation (Southall, 2023) while beta BBs (13–30 Hz) promote alertness and attention, making them candidates for cognitive enhancement (Beauchene, Abaid, Moran, Diana, & Leonessa, 2016). In children with attention deficits, theta BBs have shown mixed effects on working memory, sometimes increasing fatigue, whereas beta BBs enhance focus and response accuracy (Gao et al., 2014; Rakhshan, Hassani-Abharian, Joghataei, Nasehi, & Khosrowabadi, 2022). Preliminary evidence suggests BBs may improve language comprehension in neurotypical adults by boosting beta-band activity (Kim, Kim, Kovar, & Lee, 2023), but their application in dyslexia remains underexplored. One study reported improved speech fluency in stuttering adults via beta BBs, linked to increased left-hemispheric beta power (Chernetchenko et al., 2023), hinting at potential benefits for dyslexic children where phonological deficits predominate.

Taken together, the present study hypothesized that beta BBs would enhance reading fluency and PLV in beta-band networks involved in executive control and phonological maintenance, while theta BBs might support temporal encoding but yield lesser improvements due to potential over-relaxation effects. By employing a randomized double-blind design, this research aims to elucidate BBs' role in remediating dyslexia-related neural dysconnectivity.

2. Material and Methods

This investigation employed a randomized, controlled, exploratory design with three parallel groups to examine the influence of binaural beats on reading fluency and phase lag value (PLV) in children with dyslexia. The study was not intended to deliver any therapeutic or clinical intervention; instead, binaural beats were used exclusively as non-invasive auditory stimuli within a cognitive neuroscience framework, consistent with their application in experimental psychological and neurophysiological research.

To reduce potential sources of bias and improve methodological rigor, the study followed a randomized double-blind controlled structure. Participants were randomly allocated to one of three conditions: beta-frequency binaural beats, theta-frequency binaural beats, or a control auditory condition. Neither the participants nor the evaluators were aware of the group assignments. The control condition consisted of isochronous tones with identical frequencies presented to both ears, thereby eliminating the perception of binaural beat illusions and minimizing possible physiological entrainment effects.

Prior to the first session, both participants and their parents received a full explanation regarding the exploratory and non-clinical nature of the auditory stimulation. It was emphasized that binaural beats were used only as experimental auditory stimuli and not as a therapeutic method. Written informed consent was obtained from all participants and their parents in accordance with ethical research standards.

The study protocol was reviewed and approved by the Ethics Committee of Shahid Beheshti University (Approval Code: IR.SBU.REC.1403.052). The committee explicitly confirmed that the project does not qualify as a clinical trial according to the criteria defined by the International Committee of Medical Journal Editors, as the study involved non-invasive auditory stimulation and focused on cognitive outcomes rather than medical treatment. All procedures were conducted in accordance with the ethical principles of the Declaration of Helsinki and institutional regulations.

To evaluate possible cognitive and neurophysiological effects of beta and theta binaural beats, linguistic and electrophysiological assessments were conducted by blinded examiners. Measurements were collected at pre-test, post-test, and follow-up stages, including assessments of reading fluency, intelligence, auditory attention, visual attention, and academic performance. Post-test measurements were obtained after completion of twelve auditory stimulation sessions, and follow-up data were collected six weeks later. All experimental procedures were non-invasive and designed to ensure participant safety while maintaining data validity and minimizing experimental bias.

Participants

The sample consisted of fifty children diagnosed with dyslexia aged between 7.5 and 8.3 years (21 girls and 29 boys). The average full-scale IQ was 109 (SD = 6.16), and the Verbal Comprehension Index ranged between 95 and 115. All participants attended regular elementary schools.

Diagnosis of dyslexia had previously been established by a psychiatrist using the Dyslexia Assessment Test (DAT), which is commonly applied in Iran for identifying reading disorders. Children whose reading accuracy and fluency scores fell within the lowest 10% for their age group were classified as dyslexic and distinguished from typically developing readers.

None of the participants showed evidence of intellectual disability, cerebral palsy, or other clear neurological impairments. Persian was the first language for all participants, and all were right-handed based on a hand-preference classification procedure.

Inclusion criteria consisted of below-average reading performance combined with at least average intellectual functioning (IQ ≥ 85) and normal hearing ability. Exclusion criteria included any history of neurological disorder, psychiatric illness, epilepsy, brain injury, severe medical conditions, or genetic disorders within the individual or family.

The participants were assigned to the following groups:

One group consisted of nineteen dyslexic children who took the beta band frequency of the binaural beat (L=240 Hz, R=255 Hz). The second group included seventeen dyslexic children who took theta band frequency of binaural beat (L=240 Hz, R=245 Hz), and the last group consisted of fourteen dyslexic children who received isochronous tones (R: 240 Hz, L: 240 Hz).

Participants were asked to refrain from any caffeinated food items for at least 4 hours before testing and to get an average night's sleep. Compliance was confirmed by self-reporting and by asking about their duration of sleep.

All subjects voluntarily gave written informed consent and were informed of the test procedure

Subjects were seated in a sound and light-attenuated room, controlled at an ambient temperature of 22 degrees centigrade.

Language, attention, and intelligence tests

The group of children with dyslexia was submitted to a language test to investigate the correlation between EEG and neurolinguistic findings of dyslexia. To assess reading fluency, the reading fluency test for Children developed by Reza Nilipour was administered. This test is a standardized instrument designed to evaluate reading fluency in first grade of elementary school children. This test was assessed at the first and the last sessions of the binaural beat sessions and at follow-up.

For the general intelligence assessment, the WISC-IV was administered at the first measurement (pre-test) session.

To assess the subject's auditory and visual attention, the IVA-2 test was taken. The range of auditory attention score was from 85 to 110, and for visual attention was from 83 to 95.

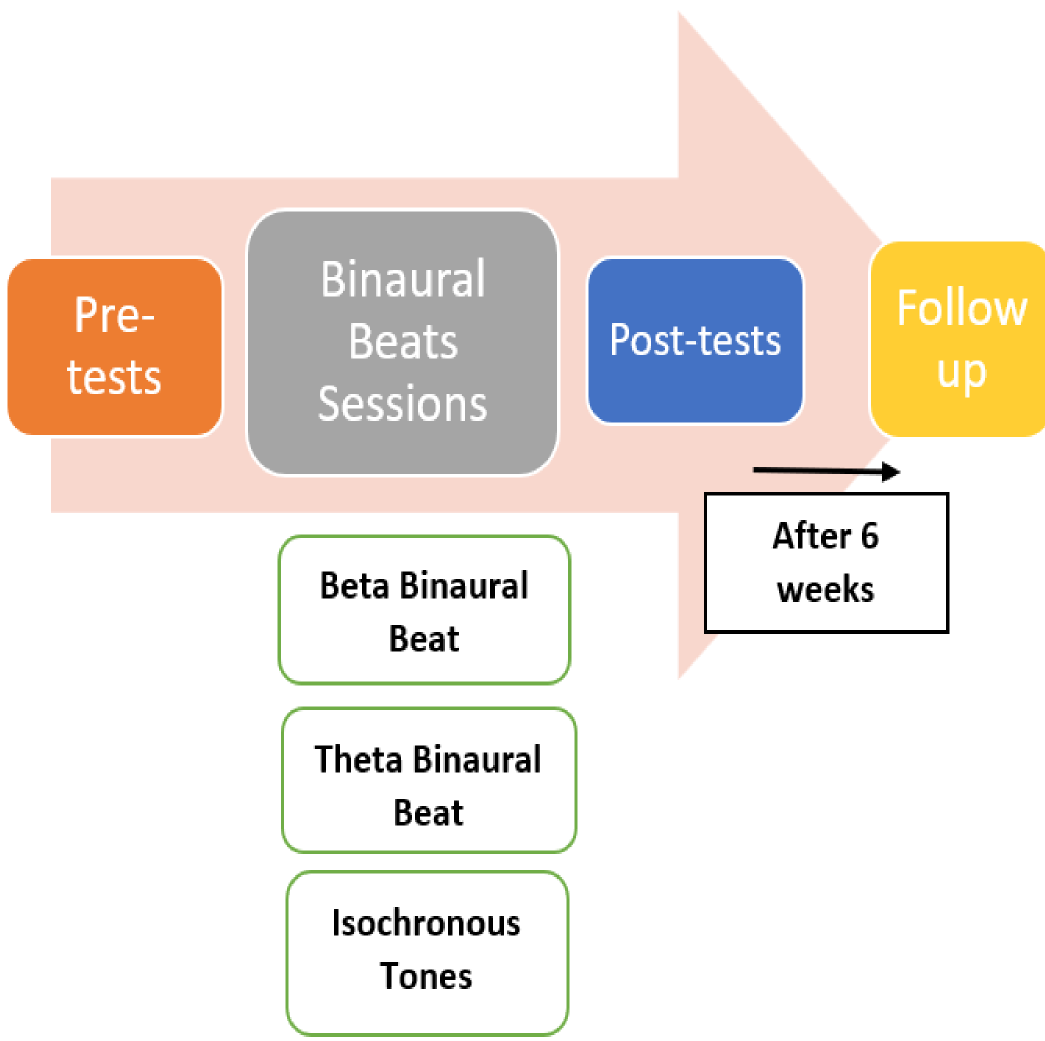
Binaural beats formation

Several auditory conditions were applied throughout the experimental sessions. The control condition consisted of isochronous tones with no interaural frequency differences, serving as an active auditory comparison rather than a true sham stimulation. Because isochronous tones still involve auditory stimulation, non-specific auditory effects cannot be completely excluded. This condition included isochronous tones (R=240 Hz, L=240 Hz). Experimental conditions included (1) a 5 Hz binaural beat as theta (L=240 Hz, R=245 Hz), and (2) a 15 Hz binaural beat as beta (L=240 Hz, R=255 Hz). The auditory signals presented to the right and left ears are indicated by R and L respectively. Stimuli were generated using Audacity software and delivered via stereo headphones (MDR-NC7, Sony). Participants adjusted the volume at the beginning of each session to a comfortable listening level while seated comfortably.

The sound pressure level (SPL) was standardized at approximately 73 dB, consistent with levels commonly used in auditory entrainment research. Volume remained constant across sessions. All participants reported that the sound intensity was comfortable and not distracting.

Each group completed twelve auditory stimulation sessions conducted three times per week. Each session lasted ten minutes. The stimulation duration was selected based on previous auditory entrainment literature indicating that short-term exposure can induce measurable oscillatory changes while minimizing fatigue, particularly in pediatric populations.

Figure 1 *Experimental Design Overview*



Electroencephalographic and data acquisition

EEG recordings were performed in a room designed to minimize both auditory and visual distractions, with ambient temperature maintained at approximately 22°C. Resting-state EEG activity was recorded under both eyes-closed and eyes-open conditions, each lasting three minutes. This duration was selected in accordance with standard neurophysiological recommendations to ensure adequate data length for reliable spectral and functional connectivity analyses. Previous literature suggests that recordings of at least three minutes provide sufficiently stable neural oscillatory patterns while reducing the influence of transient fluctuations.

During the eyes-open condition, participants were instructed to remain relaxed and visually fixate on a red point displayed on a computer monitor in order to limit eye movement artifacts and maintain attentional consistency across subjects. EEG signals were collected using the international 10–20 electrode placement system with standard silver–silver chloride electrodes.

Nineteen scalp channels were recorded using a Quik-Cap system connected to the NuAmps amplifier following the 10–20 configuration (FP1, FP2, F3, F4, F7, F8, Fz, C3, C4, Cz, P3, P4, Pz, T3, T4, T5, T6, O1, O2). Earlobe electrodes (A1 and A2) served as reference channels, and the ground electrode was placed at Cz. Electrode impedance for all channels was maintained below 10 kΩ to ensure signal quality.

Signals were sampled at 250 Hz. Hardware filters included a 0.5 Hz high-pass filter to remove slow drift and a 30 Hz low-pass filter to eliminate high-frequency noise. Power line interference at 60 Hz was also attenuated during preprocessing.

EEG recordings were conducted at three time points: prior to the onset of binaural beat sessions (baseline), immediately after completion of the intervention sessions, and during a follow-up stage six weeks later. The follow-up assessment was included to examine whether any electrophysiological or cognitive changes persisted over time and to compare post-intervention patterns with baseline neural activity.

EEG signal preprocessing and Functional connectivity analyses

EEG preprocessing followed a standardized multistep procedure. Raw signals were initially inspected visually and then screened using automated artifact detection algorithms. Eye-blink and movement artifacts were removed through a combination of automatic rejection and manual verification to improve data quality.

Continuous EEG data were segmented into epochs of two seconds, and only artifact-free segments were retained for subsequent analyses. On average, between 70 and 85 valid epochs per participant were included. Signals were re-referenced to the common average reference prior to connectivity analysis. Band-pass filtering was then applied separately for the theta (4–8

Hz) and beta (13–30 Hz) frequency ranges.

Functional connectivity was quantified using Phase Lag Value (PLV), calculated from the band-pass filtered signals in the theta and beta bands. PLV estimation was performed across all electrode pairs using artifact-free epochs. The computational procedure followed the method described by Jean-Philippe Lachaux and colleagues (1999), where phase synchronization between signals is derived from the consistency of instantaneous phase differences across time (Lachaux, Rodriguez, Martinerie, & Varela, 1999):

$$PLV = | (1/N) \Sigma \exp(i\Delta\varphi(t)) |$$

In this formula, $\Delta\varphi(t)$ denotes the instantaneous phase difference between two EEG signals at each time point.

Statistical analyses

An a priori statistical power analysis was conducted using the software G*Power (version 3.1) for a repeated-measures ANOVA design with three groups and three measurement stages. Assuming a medium effect size ($f = 0.25$), a significance level of 0.05, and statistical power of 0.80, the minimum required sample size was estimated at 42 participants. Accordingly, the final sample of 50 participants was considered adequate for detecting group differences.

Descriptive statistics including mean values, standard deviations, and score ranges were computed for both electrophysiological and language-related measures (including phonological working memory) across pre-test, post-test, and follow-up stages.

Before inferential analysis, statistical assumptions were evaluated. Data normality was examined using the Shapiro–Wilk test, and homogeneity of variance across groups was assessed using Levene’s test. Additionally, the Kruskal–Wallis test was applied to verify group comparability at baseline.

A mixed-design analytical framework was implemented. Repeated-measures ANOVA was used for EEG connectivity variables, with Time (pre-test, post-test, follow-up) as the within-subject factor and Group (beta, theta, control) as the between-subject factor. For behavioral variables that did not meet parametric assumptions, the Friedman test was employed. Furthermore, analysis of covariance (ANCOVA) was conducted on post-test outcomes using baseline scores as covariates to control for initial differences. Statistical significance was defined at $p < 0.05$.

Because connectivity analyses were performed across multiple frequency bands and electrode pairs, the risk of Type I error due to multiple comparisons increased. To address this issue, False Discovery Rate (FDR) correction was applied using the Benjamini–Hochberg procedure within each frequency band.

All statistical analyses were carried out using IBM SPSS Statistics (version 27).

3. Results

The analysis showed distinct patterns of change in reading fluency and EEG connectivity across the three groups. As depicted in Figure 3, reading fluency (measured as words per minute) showed substantial improvement in the beta binaural beat group from pre-test ($M = 32.5$, $SEM = 3.9$) to post-test ($M = 78.4$, $SEM = 3.8$) and follow-up ($M = 82.1$, $SEM = 4.1$), with a repeated-measures ANOVA indicating a significant Time × Group interaction ($F(4,94) = 12.45$, $p < 0.001$, $\eta^2 = 0.35$). Post-hoc comparisons confirmed that the beta group's gains were significantly greater than those in the theta (post-test: $M = 45.2$, $SEM = 5.1$; follow-up: $M = 48.7$, $SEM = 4.9$) and control groups (post-test: $M = 38.9$, $SEM = 4.7$; follow-up: $M = 40.3$, $SEM = 5.0$; all $p < 0.01$, Bonferroni-corrected). No significant differences were observed between theta and control groups ($p > 0.05$).

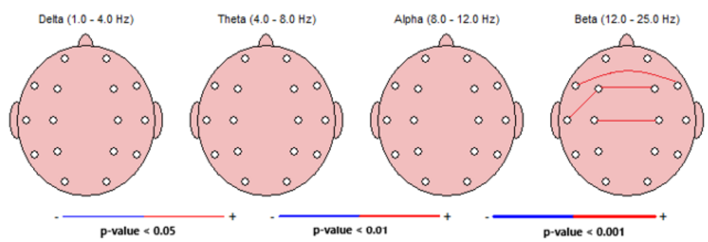
Topographic representations in Figure 2 illustrated frequency-specific PLV alterations post-stimulation. In the beta group (Figure 2a), increased PLV (red lines) was prominent in beta (12–25 Hz) and theta (4–8 Hz) bands across left-hemispheric electrode pairs, such as F3–T3 and F3–P7, indicating enhanced connectivity in phonological networks. The theta group (Figure 2b) showed moderate increases in theta-band PLV in temporo-parietal regions (e.g., T3–P7), while the control group (Figure 2c) exhibited no changes.

Table 1 summarized significant PLV changes (FDR-corrected, $p < 0.05$), highlighting increases in beta-band connectivity for fronto-central executive (Fz–Cz) and left fronto-temporal phonological networks (F3–T3, F3–P7) under eyes-open conditions in the beta group. Theta-band increases were noted in temporal encoding (Cz–T3) and temporo-parietal phonological networks (T3–P7) under eyes-closed conditions, primarily in the beta and theta groups. ANCOVA, controlling for baseline scores, confirmed group effects on post-test PLV ($F(2,47) = 8.67$, $p = 0.001$, $\eta^2 = 0.27$), with beta stimulation yielding the strongest enhancements.

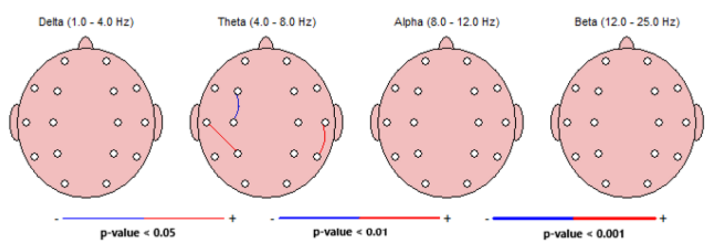
Figure 2. *Topographic representations of EEG Phase Lag Value (PLV) changes in children with*

dyslexia across three experimental conditions (a: beta binaural beat group, b: theta binaural beat group, c: control group). The figure displays four scalp maps corresponding to the delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), and beta (12–25 Hz) frequency bands. Significant alterations in PLV are illustrated as connection lines between electrode pairs, with color coding based on statistical thresholds (red indicating increased PLV and blue indicating decreased PLV). Electrode locations are marked by dots according to the standard scalp montage. Connectivity patterns are shown for the following electrode combinations: FP1–F3, FP1–C3, FP1–P3, FP1–O1, FP1–F7, FP1–T3, FP1–T5, F3–C3, F3–P3, F3–O1, F3–F7, F3–T3, F3–T5, C3–P3, C3–O1, C3–F7, C3–T3, C3–T5, P3–O1, P3–F7, P3–T3, P3–T5, O1–T3, O1–T5, F7–T3, F7–T5, and T3–T5. The maps illustrate frequency-specific PLV modifications following binaural beat exposure across the beta, theta, and control groups, with the most prominent changes observed in the theta and beta bands, which are functionally associated with language-related neural processing.

(a)



(b)



(c)

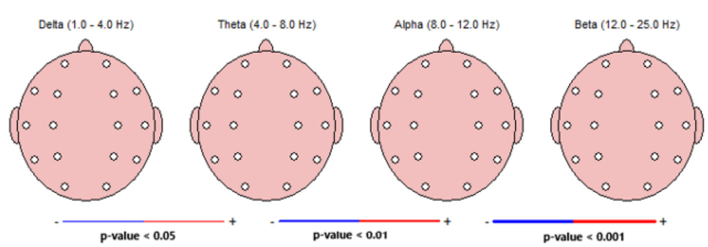


Figure 3 *Changes in reading fluency (words per minute) across pre-test, post-test, and follow-up stages in the three groups: Beta Binaural Beat Group (green), Theta Binaural Beat Group (blue), and Control (Sham) Group (yellow). Bars represent mean ± standard error of the mean (SEM). The Beta Binaural Beat group showed substantial improvement in post-test and follow-up.*

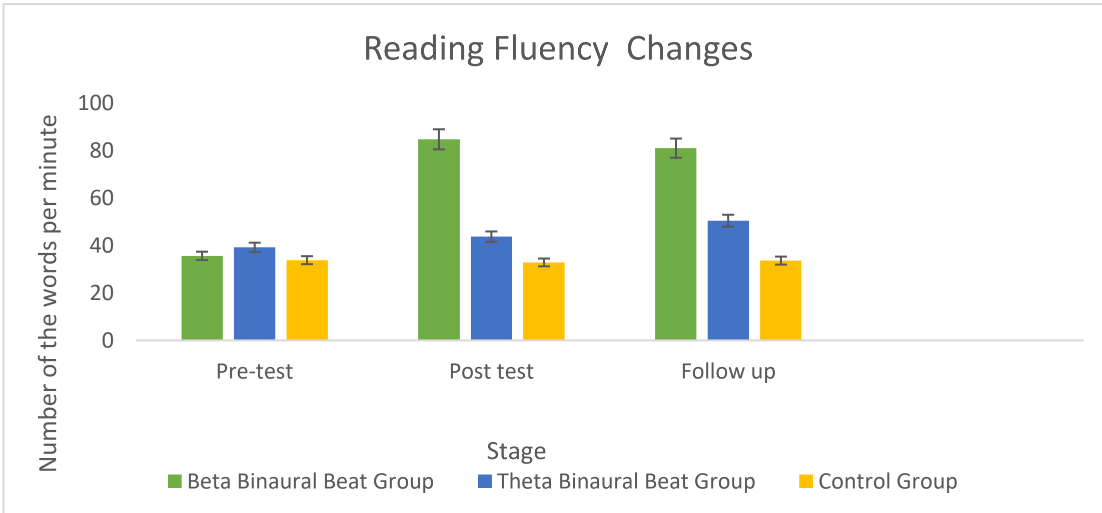


Table1 *Significant Changes in Phase Lag Value (PLV) After Binaural Beat Stimulation (FDR Corrected)*

Frequency Band	Electrode Pair	Condition	Direction	p-value (FDR)	Network Interpretation
Beta (13–30 Hz)	Fz–Cz	Eyes Open	Increase	<0.05	Fronto-central executive network
Beta (13–30 Hz)	F3–T3	Eyes Open	Increase	<0.05	Left fronto-temporal phonological network
Beta (13–30 Hz)	F3–P7	Eyes Open	Increase	<0.05	Phonological maintenance network
Theta (4–8 Hz)	Cz–T3	Eyes Closed	Increase	<0.05	Temporal encoding network
Theta (4–8 Hz)	T3–P7	Eyes Closed	Increase	<0.05	Temporo-parietal phonological network

4. Discussion

The present study provides the first controlled evidence that short-term exposure to beta-frequency binaural beats (15 Hz) significantly enhances reading fluency and cortical phase synchronization (measured by Phase Lag Value, PLV) in children with developmental dyslexia, with effects persisting at a six-week follow-up. In contrast, theta-frequency binaural beats (5 Hz) produced only modest behavioral gains and limited connectivity changes, while the isochronous tone control condition yielded no substantial improvements. These differential outcomes support the hypothesis of frequency-specific neural entrainment, whereby beta stimulation modulates oscillatory dynamics in language-related networks to alleviate core deficits in phonological processing and reading fluency (Colling, Noble, & Goswami, 2017; Goswami, 2011).

Behavioral Outcomes: Improvements in Reading Fluency

The beta binaural beat group exhibited a marked increase in reading fluency, from a pre-test mean of approximately 33 words per minute to 82 words per minute at follow-up, as assessed by the Nilipour Reading Fluency Test. This large effect was confirmed by a significant Time × Group interaction in repeated-measures ANOVA ($F(4,94) = 12.45$, $p < 0.001$, $\eta^2 = 0.35$), with post-hoc tests showing enhancement relative to both the theta and control groups ($p < 0.01$, Bonferroni-corrected). These results indicate not only accelerated word recognition but also sustained fluency, suggesting transfer to real-world reading demands.

Such enhancements align with emerging evidence that beta-frequency auditory stimulation supports cognitive functions critical for reading, including attention and phonological integration (Beauchene et al., 2016; Kim et al., 2023).Beta binaural beats have been shown to improve sentence comprehension accuracy and speed, particularly for complex structures, by modulating neural activity during language processing (Kim et al., 2023). In dyslexia, where fluency deficits often caused by inefficient phonological decoding and rapid automatization(Shaywitz & Shaywitz, 2005) , beta entrainment may facilitate faster grapheme-phoneme mapping and reduce cognitive load during text reading (Keshavarzi et al., 2024). The persistence of enhancement at six weeks further implies neuroplastic changes rather than transient arousal effects, consistent with studies demonstrating lasting improvements in attention and memory following beta stimulation.

Conversely, the theta group's limited progress (from ~33 to ~49 words per minute) mirrors findings that theta binaural beats (4–8 Hz) enhance relaxation and memory consolidation but cannot affect sustained attention and working memory in demanding tasks (Ingendoh, Posny, & Heine, 2023). In dyslexic children, who frequently exhibit increased theta power associated with attentional lapses (Cainelli, Vedovelli, Carretti, & Bisiacchi, 2023), additional theta entrainment may exacerbate fatigue without benefiting active phonological processing. The control group's lack of change confirms that effects are attributable to the binaural illusion (interaural frequency difference) rather than non-specific auditory input, as isochronous tones do not induce entrainment (Oster, 1973).

These behavioral patterns resonate with oscillation-based models of dyslexia, which propose that impaired entrainment to rhythmic speech cues disrupts syllable-level phonological segmentation and reading fluency (Colling et al., 2017; Goswami, 2011). Interventions enhancing temporal precision, such as rhythmic training, have similarly enhanced reading outcomes by improving low-frequency synchronization (Bhide, Power, & Goswami, 2013; Flaugnacco et al., 2015). Our use of beta beats may have compensated for these deficits by amplifying higher-frequency oscillations that support rapid, precise processing.

Neurophysiological Outcomes: PLV Increases and Network Reorganization

The EEG results showed frequency- and group-specific PLV changes, with the beta group showing significant increases (FDR-corrected $p < 0.05$) in beta-band connectivity within fronto-central (Fz–Cz), left fronto-temporal (F3–T3), and phonological maintenance networks (F3–P7) during eyes-open resting state. Theta-band PLV enhancements occurred in temporo-parietal (T3–P7) and temporal encoding networks (Cz–T3) under eyes-closed conditions, though more prominently in the beta group. Topographic maps (Figure 2) illustrated these alterations as red connection lines in language-relevant hubs, indicating strengthened phase synchronization.

PLV, a robust index of lagged phase coupling that minimizes volume conduction artifacts (Stam, Nolte, & Daffertshofer, 2007), is particularly sensitive to functional dysconnectivity in dyslexia. Prior studies report reduced PLV in left-hemispheric theta and beta bands among dyslexic individuals, reflecting impaired integration in phonological and executive networks (Castillo-Barnes et al., 2024; Fraga González et al., 2018; Žarić et al., 2017). Our findings suggest that beta binaural beats induce entrainment that reorganizes these networks, enhancing left-lateralized phonological processing and fronto-central executive control (Cainelli et al., 2023; Formoso, Ortiz, Martinez-Murcia, Gallego, & Luque, 2021). The fronto-temporal increases likely support the phonological loop in verbal working memory, while temporo-parietal enhancements facilitate auditory-temporal integration essential for phoneme discrimination (Dushanova, Lalova, Kalonkina, & Tsokov, 2020).

The differential effects, stronger beta-band changes in the beta group, align with frequency-specific entrainment principles: beta oscillations promote active, alert states conducive to cognitive tasks, whereas theta supports introspective or consolidative processes (Beauchene et al., 2016). The sustained PLV elevations at follow-up imply enduring plasticity, possibly via strengthened synaptic efficacy in entrained circuits (Chernetchenko et al., 2023).

Mechanisms: Neural Entrainment and Oscillatory Compensation

These outcomes are best explained by auditory-driven neural entrainment, where binaural beats generate periodic stimulation that phase-locks cortical oscillators to the beat frequency (Beauchene et al., 2016; Oster, 1973). In dyslexia, atypical entrainment to speech envelopes impairs phonological segmentation (Colling et al., 2017; Dushanova et al., 2020). Beta stimulation (15 Hz) may reset oscillatory imbalances by enhancing cross-frequency coupling (e.g., theta-gamma nesting for phoneme encoding), counteracting the "neural noise" hypothesis of dyslexia

(Gallego-Molina, Ortiz, Arco, Martinez-Murcia, & Woo, 2024; Glica et al., 2025).

Theta effects were weaker, consistent with reports of fatigue or reduced vigilance following low-frequency stimulation (Ingendoh et al., 2023). The persistence of changes suggests long-term potentiation-like mechanisms, as seen in auditory training studies that normalize connectivity and improve reading (Stam et al., 2007).

Comparisons with Existing Literature

Our results extend prior work on binaural beats in cognitive enhancement. Beta beats improve visuospatial working memory and cortical connectivity (Beauchene et al., 2016), while beta/gamma stimulation enhances language comprehension (Kim et al., 2023). In fluency-related disorders, beta beats reduce disfluency in stuttering by boosting left-hemispheric beta power (Chernetchenko et al., 2023). For dyslexia, though direct binaural beat studies are scarce, rhythmic interventions that entrain oscillations improve phonological awareness and reading via enhanced connectivity (Bhide et al., 2013; Flaugnacco et al., 2015).

PLV findings converge with dyslexia research showing alpha/beta dysconnectivity (Fraga González et al., 2018) and remediation through training (Stam et al., 2007). Discrepancies with null binaural beat effects (Ingendoh et al., 2023) may reflect differences in protocol (e.g., session length, carrier frequency) or population (our pediatric dyslexic sample vs. neurotypical adults).

Limitations

The sample size (N=50), while powered adequately, limits subgroup analyses (e.g., by gender or dyslexia severity). Resting-state EEG provides baseline insights but not task-specific dynamics; future work should include reading-related paradigms. The active control (isochronous tones) minimizes non-specific effects but cannot rule out subtle auditory influences. Exclusion of comorbidities enhances internal validity but reduces ecological validity. Persian orthography (transparent) emphasizes fluency deficits, potentially limiting generalization to opaque scripts like English.

Implications and Future Directions

Beta binaural beats emerge as a promising, non-invasive adjunct for dyslexia remediation, targeting neural dysconnectivity with low cost and minimal risk. Integration with phonological training could accelerate fluency gains, particularly in resource-limited settings. Personalized protocols (e.g., based on baseline EEG) warrant exploration (Glica et al., 2025).

Future studies should: (a) use larger, longitudinal designs with longer follow-ups; (b) incorporate task-based EEG/fMRI; (c) compare with established interventions (e.g., neurofeedback, music therapy); and (d) test in diverse linguistic contexts.

In conclusion, beta binaural beats are enhancing oscillatory synchrony and reading fluency, paving the way for innovative auditory-based therapies.

5. Conclusion

In summary, beta binaural beats offer a promising, non-invasive method to enhance reading fluency and cortical connectivity in dyslexic children, with PLV increases in key language networks underscoring neural entrainment as a mechanism. Future research should explore long-term effects and integration with educational interventions to optimize outcomes for dyslexia.

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Author contributions

Conceptualization: Noushin Sangtarash, Mohammad Reza Bigdeli
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Investigation: Noushin Sangtarash, Mohammad Ali Nazari
Formal Analysis: Noushin Sangtarash, Mohammad Reza Bigdeli
Writing – Original Draft: Noushin Sangtarash
Writing – Review & Editing: Mohammad Reza Bigdeli, Mohammad Ali Nazari, Jalil Fathabadi
Supervision: Mohammad Reza Bigdeli
Resources: Mohammad Ali Nazari
Project Administration: Mohammad Reza Bigdeli

Conflict of Interest

The authors declare no competing interests.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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