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Enhancing Left Hemisphere Function in Dyslexia: A Pilot Study on 14-Channel Neurofeedback With Auto Train Brain

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Abstract

Dyslexia is a neurodevelopmental disorder characterized by difficulties in reading comprehension and speed despite normal intelligence. Neurofeedback training has emerged as a promising intervention to enhance cognitive function in individuals with dyslexia. This study aimed to evaluate the impact of Auto Train Brain, a neurofeedback-based mobile application, on gamma band entropy variance, a measure of neural signal complexity in children aged 7–10 diagnosed with dyslexia. Over the course of 30 and 100 neurofeedback sessions, using the EMOTIV INSIGHT (5 channels) and EPOC-X (14 channels) headsets, we analyzed electrophysiological changes to assess neural adaptability. Prior research has established left hemisphere deficits in dyslexia, and neurofeedback has been shown to modulate brain activity. Our findings indicate that both session duration and headset configuration influenced gamma band entropy variance, with longer training (100 sessions) and higher channel count (14) yielding greater improvements in the left temporal lobe. These results suggest enhanced functional neural adaptability, highlighting neurofeedback's potential as a long-term intervention for improving left hemisphere functionality in children with dyslexia.

Keywords: neurofeedback; sample entropy; learning disorders; dyslexia; EEG; gamma band; brain lateralization; neuroplasticity; reading skills; mobile application

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Introduction

Dyslexia is defined by the DSM-V as a specific learning disorder that predominantly affects reading capabilities in individuals with normal or above-average intelligence. The etiology of dyslexia has been extensively studied, with research indicating a strong genetic basis. However, conflicting theories exist regarding the relative contributions of genetic and environmental factors to dyslexia. For instance, while studies such as (Eroglu, 2022) emphasize hereditary predisposition based on familial patterns, others argue that environmental influences like maternal stress and prenatal infections play an equally significant role in neurodevelopmental disruptions (Bale, 2016; Kundakovic & Jaric, 2017). These debates highlight the complexity of dyslexia's etiology and underscore the need for integrative approaches that account for both genetic and environmental factors.

The theoretical framework for this study is grounded in neurodevelopmental deficits and hemispheric asymmetry, which are commonly observed in dyslexic individuals. Neurodevelopmental deficits are primarily characterized by difficulties in phonological processing, such as impairments in manipulating speech sounds and retrieving phonological representations from long-term memory. These deficits are compounded by atypical brain lateralization patterns, which may exacerbate reading difficulties. The theory posits that inefficient brain lateralization, particularly in the left hemisphere, contributes to the disrupted reading network and functional connectivity observed in dyslexia.

Dyslexia is marked by hypoactivation within the reading network, disrupted functional connectivity, and differences in structural connectivity within

certain fiber tracts (Kuhl et al., 2020). Despite receiving educational support, dyslexic children often struggle to close the learning gap with their peers and these challenges can persist into adulthood (Reid, 2018). Thus, the study aimed to test the hypothesis that neurofeedback can modulate brain lateralization, particularly in the left hemisphere, to enhance language processing and reading fluency in dyslexic individuals.

Phonological processing deficits, including difficulty with manipulating speech sounds and retrieving phonological representations, are common in dyslexia. These challenges are compounded by brain lateralization inefficiencies, particularly in the left hemisphere, which disrupt reading and language processing. For example, Simos et al. (2011) identified disrupted interhemispheric communication as a contributing factor to these difficulties. However, alternative perspectives suggest that delayed brain maturation may be a more critical driver of functional connectivity deficits (Chyl et al., 2021; Pellegrino et al., 2023). Such conflicting findings necessitate deeper examination of neural mechanisms underlying dyslexia.

In the left temporal lobe, this disconnection is reflected in increased slow-wave activity on qEEG measurements, indicating delayed brain maturation and functional connectivity deficits (Kuhl et al., 2020). A growing body of research suggests that dyslexia is associated with inefficient brain lateralization rather than being purely a phonological disorder. For instance, Chyl et al. (2021) demonstrated reduced left-hemisphere dominance in dyslexic individuals, affecting language processing and reading fluency. Conversely, other studies propose that incomplete lateralization before school age may exacerbate reading difficulties but emphasize early intervention as a mitigating factor (Eroğlu, 2020; Weiss et al., 2022). These divergent theories illustrate ongoing debates regarding whether lateralization inefficiencies are causal or secondary to dyslexia symptoms.

One promising intervention is neurofeedback, which has been theorized to improve brain lateralization and functional connectivity by directly modulating neural activity. Neurofeedback offers a unique mechanism for addressing these brain asymmetries and enhancing the left-hemisphere dominance critical for language processing. This study compares the efficacy of 30-session versus 100-session neurofeedback with Auto Train Brain to existing neurofeedback interventions, particularly those utilizing 5-channel versus 14-channel EEG headsets. Previous findings suggest that a minimum of 30–50 sessions is required for stable neurophysiological changes, while 100+ sessions enhance retention of improvements. Additionally, multichannel neurofeedback, such as the 14-channel EEG system used in this study, may provide a more detailed and effective analysis of neural activity compared to 5-channel systems. Despite the growing interest in neurofeedback for dyslexia, studies focusing on multisession and multichannel neurofeedback are relatively scarce. This study hypothesizes that neurofeedback, specifically with the Auto Train Brain system, can improve left-lateralized brain activity, thereby addressing the underlying neural deficits contributing to dyslexia.

Auto Train Brain is an advanced neurofeedback solution that integrates 14-channel EEG neurofeedback with cognitive training methods, distinguishing it from traditional approaches that typically use fewer channels or less dynamic systems. It utilizes machine learning algorithms to optimize intervention effectiveness. Previous studies on Auto Train Brain have demonstrated that neurofeedback training can increase gamma band entropy variance, reflecting improved neural adaptability and functional connectivity. Furthermore, recent findings suggest its potential for enhancing left-hemisphere lateralization—a critical aspect of language processing in dyslexics (Nora et al., 2021). By situating this study within ongoing debates about neural plasticity and lateralization inefficiencies in dyslexia research, it fills a gap by exploring the specific benefits of multisession, multichannel neurofeedback and its ability to target complex neural dysfunctions more comprehensively than single-channel systems.

This study aimed to evaluate the efficacy of 30-session versus 100-session neurofeedback training with 5-channel versus 14-channel EEG headsets using Auto Train Brain in improving left-hemisphere lateralization and functional connectivity in dyslexics. By explicitly testing the hypothesis that neurofeedback can enhance left-hemisphere lateralization, this study seeks to clarify the relationship between hemispheric asymmetry and dyslexia symptoms, contributing to the development of more effective intervention strategies. The findings may also provide evidence for resolving conflicting theories regarding genetic versus environmental contributions by demonstrating how targeted neural interventions can modulate cortical activity irrespective of etiological origins.

Materials and Methods

Subjects and Experimental Data

In this experiment, 40 dyslexic children participated, with 20 assigned to the experimental group and 20 to the control group. Written consent was obtained from all participants and their families in accordance with the rules set by the research ethics committee. Their ages ranged from 7 to 10, with a gender distribution of 34 males and 6 females. The gender imbalance reflects the higher prevalence of dyslexia in males, which has been widely documented in epidemiological studies. The recruitment period was 6 months.

The children in the experimental group were diagnosed with dyslexia by psychiatric professionals, who then recommended that their families use Auto Train Brain at home. Psychologists and psychiatrists used the Test of Integrated Language and Literacy Skills (TILLS) to examine whether the individuals met the DSM-V dyslexia criteria. Randomization was achieved by enrolling participants sequentially as they met the inclusion criteria, and they were assigned to the experimental group in a nonbiased manner. The control group consisted of children who met the same dyslexia criteria but did not receive neurofeedback training. The experimental group underwent neurofeedback training using Auto Train Brain, whereas the control group did not receive any intervention. Baseline qEEG data and TILLS scores were recorded for both groups prior to the start of the intervention, and posttreatment assessments were conducted after completing 30 or 100 sessions, depending on the experimental condition, to measure changes.

The study's inclusion criteria stipulated that participants must be of middle socioeconomic status, be drug-free, have dyslexia as their only comorbid condition, and be aged between 7 and 10. They lived across various cities in Turkey. Scientific justifications for these criteria are as follows: the age range of 7–10 years was selected as this is a critical period for reading acquisition and neuroplasticity, making early intervention more effective. Middle socioeconomic status was chosen to minimize confounding effects, as lower-income children may have educational disadvantages unrelated to dyslexia, while higher-income children may have access to additional remedial support. Participants were required to be drug-free as medications, such as stimulants used for ADHD, can alter EEG patterns and confound neurofeedback effects. Finally, limiting participation to children with dyslexia as the only comorbid condition ensures that the intervention's effects are not influenced by other neurodevelopmental disorders like ADHD or ASD, which have distinct electrophysiological signatures.

The socioeconomic status of participants was assessed using a structured parental survey, which collected information on employment type (e.g., staff, blue-collar, or white-collar workers), education level (e.g., elementary, secondary, and postsecondary), and income brackets (low income <6,000 TL, middle income 6,000–20,000 TL, high income >20,000 TL).

A baseline qEEG assessment was conducted for both experimental and control groups to establish initial neurophysiological states. The intervention group then engaged in 30 or 100 neurofeedback sessions, depending on group assignment, while the control group did not receive neurofeedback but completed the same assessments at the end of the study to control for test–retest effects.

We calculated a priori power to predict the sample size using G*power. We set the effect size as 0.63, which was calculated from the pre- and post-TILLS descriptive scores of the experimental group without comorbidities in the original clinical trial of Auto Train Brain. The alpha value was set at .05, with a power (1-beta) of .95, and a *t*-test and RCT as input parameters. The required sample size was determined to be 67 per group. However, as this is a pilot study, a smaller sample size (40 participants in total) was selected to assess feasibility and preliminary effects. The results of this study will inform the design and power analysis of a future large-scale randomized controlled trial.

QEEG Recording

In the experiments, EMOTIV INSIGHT2 and EPOC-X headsets were used. The EEG data were recorded at 2048 samples per second per channel, downsampled to 128 samples per second per channel. Downsampling was performed to optimize signal processing efficiency while retaining relevant spectral information. EEG data were converted to frequency band data using EMOTIV's standard procedures. The frequency band were defined as: theta (4–8 Hz), alpha (8–12 Hz), beta-1 (12–16 Hz), beta-2 (16–25 Hz), and gamma (25–45 Hz). Artifact rejection was implemented using an adaptive thresholding method to remove nonneural signals (e.g., eye blinks, muscle activity). Additionally, a high-pass filter (>100 Hz) was applied to remove low-frequency drifts and ensure a cleaner gamma band signal. This cutoff was chosen based on prior

studies indicating that frequencies above 100 Hz are predominantly nonneuronal noise.

The EMOTIV APP was used for headset calibration, ensuring optimal electrode conductivity. Calibration included impedance checking to ensure all electrode connections remained below 5 kΩ, improving signal quality and reducing interference.

The recorded channels AF3, T7, P7, T8, and AF4 for EMOTIV INSIGHT2 (5 channels), and AF3, F3, F7, FC5, T7, P7, O1, O2, P8, T8, FC6, F8, F4, and AF4 for EMOTIV EPOC-X (14 channels). The EMOTIV EPOC-X consists of 14 sensors with felt pads inserted in the scalp per the International 10–20 system (AF3, F3, F7, FC5, T7, P7, O1, AF4, F4, F8, FC6, T8, P8, and O2). As reference channels, and reference electrodes placed on the mastoids. Saline liquid solution was applied to improve conductivity, and the sampling frequency was set at 128 Hz. Each sensor placement followed the 10–20 system to ensure replicability and consistency with established neurofeedback protocols.

To assess the impact of neurofeedback training, qEEG measurements were taken before the intervention, after 30 sessions, and at the end of 100 sessions for the experimental group. The control group was assessed at the same time points to compare changes due to neurofeedback.

Neurofeedback Treatment Protocol and Multisensory Learning Method

Auto Train Brain is a mobile application that uses neurofeedback and multisensory learning principles. It is used with the EMOTIV EPOC+ headset. It is a noninvasive solution that improves brain performance for adults and children without any side effects. It reads qEEG from 5 or 14 channels, depending on the headset used, processes these signals, and provides real-time visual and auditory online neurofeedback. Auto Train Brain is a patented software (patent number: PCT/TR2017/050572) specifically designed for people with dyslexia.

The EEG neurofeedback protocol is as follows:

- Reduce theta waves at the Broca area in the brain if they exceed a threshold of 4.5 μV, determined through baseline qEEG analysis.
- Reduce theta waves at the Wernicke area in the brain if they exceed a threshold of 4.8 μV.
- Identify channels with the highest absolute theta power (above 5 μV) in the left hemisphere and reduce absolute theta for those channels.
- Identify channels with the highest absolute theta power (above 5.2 μV) in the right hemisphere and reduce absolute theta for those channels.

A positive reward was displayed as a green arrow, while negative feedback was indicated by a red arrow and a “beep” sound. The reward timing was set to reinforce positive changes every 250 ms, aligning with previous neurofeedback studies indicating optimal reinforcement rates (Enriquez-Geppert et al., 2013). A phoneme-grapheme matching alphabet teaching system was introduced after each neurofeedback session.

Multisensory learning complements neurofeedback by reinforcing auditory and visual processing simultaneously. Research suggests that integrating phonological training with neurofeedback enhances reading outcomes in dyslexic children (Breteler et al., 2010). Following neurofeedback, participants engaged in a 15-min structured alphabet learning exercise that included visual letter recognition, auditory phoneme identification, and kinesthetic letter tracing, ensuring engagement of multiple sensory modalities.

Study Design

All subjects used Auto Train Brain (a mobile phone application) more than 100 times. The selection of 100 sessions was based on prior evidence indicating that a minimum of 30–50 sessions is required for stable neurophysiological changes (Nazari et al., 2012; Perronnet et al., 2016), while extended training (100+ sessions) enhances retention of improvements in dyslexic children (Breteler et al., 2010).

Participants were assigned to two conditions: 20 participants had their brain waves recorded using EMOTIV INSIGHT for 5 channels, while 20 had their brain waves recorded using EMOTIV EPOC-X for 14 channels. Both groups received visual and auditory neurofeedback for 30 min per session, a duration chosen based on studies demonstrating that neurofeedback sessions lasting between 20–40 min yield optimal cognitive and neural improvements (Arns et al., 2014; Steiner et al., 2014). The session was followed by 15 min of multisensory alphabet learning.

Parents were instructed to ensure a controlled training environment at home, including maintaining a 40 cm distance between the subject and the smartphone application screen. Each participant

independently used Auto Train Brain's arrow neurofeedback interface under parental supervision.

At the end of each session, session average data for each frequency band was saved to the database. During the neurofeedback session, sample entropy was calculated for each frequency band data. Sample entropy, a measure of neural signal complexity, was computed for qEEG data as raw EEG data were not accessible from EMOTIV INSIGHT2 or EPOC-X.

The feature set consists of 5 variables mapped from 5 channels for EMOTIV INSIGHT and 14 variables mapped from 14 channels for EMOTIV EPOC-X. The measures are gamma band sample entropy values calculated from qEEG band power values.

Ethical Approval

This study was conducted in accordance with the ethical principles outlined in the Helsinki Declaration. The study protocol was approved by the Ethics Committee of Yeditepe University, and the clinical trial was registered with the Turkey Pharmaceuticals and Medical Devices Agency (Registration Number: 71146310-511.06, dated 2.11.2018). Informed consent was obtained from all participants' parents or legal guardians. The consent process included a detailed explanation of the study objectives, procedures, potential risks, and benefits. Additionally, assent was obtained from all child participants aged 7–10. The assent process involved using age-appropriate language to ensure children understood their participation was voluntary and they could withdraw at any time. Researchers explained the study using visual aids and interactive discussions to facilitate comprehension. Furthermore, a neutral third-party psychologist was present during the consent and assent process to ensure ethical compliance and that children were not coerced.

Beyond the ethics committee registration, oversight mechanisms included periodic audits by an independent review board to ensure adherence to ethical guidelines and data protection measures. Confidentiality was maintained by anonymizing participant data, and no personally identifiable information was stored.

Statistical Analysis

The statistical analysis was performed with SPSS 22. The regression analysis has been performed and R^2 values are reported. The increase in the variance of gamma band entropy (y-axis) in the left posterior region in the 100 sessions (x-axis, 1 bin = 10 sessions) was tested for the significance of the regression slope coefficient. It was checked whether our model is a significant predictor of the outcome variable using the results of ANOVA for regression (The change in the variance of gamma band entropy [y-axis] in the left [T7] and right temporal [T8] regions versus session groups [x-axis]).

Results

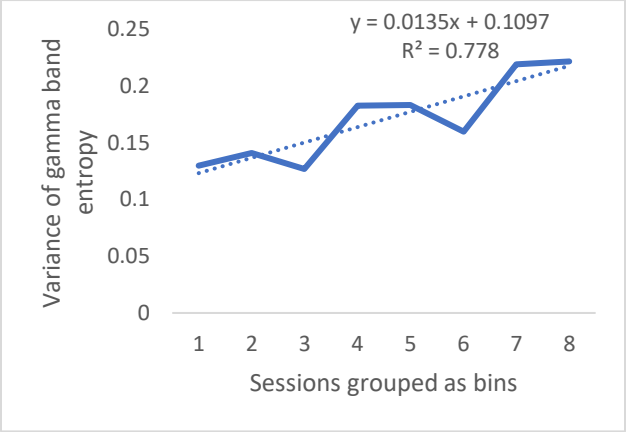
Left Hemispheric Lateralization Progression During Neurofeedback Training

Figure 1 illustrates the progression of left hemispheric lateralization in dyslexic participants throughout neurofeedback training sessions using the Auto Train Brain system. The graph depicts a scatter plot with a linear trendline, where the x-axis represents the sessions grouped into bins (1–8), and the y-axis shows the variance of gamma band entropy. The increasing trend in left lateralization is accompanied by fluctuations in individual data points, indicating variability in participant responses to the intervention. Some outliers are observed in the early and middle training phases, suggesting differing adaptation rates across individuals. The positive slope of the trendline ($y = 0.0135x + 0.1097$) indicates a general increase in left lateralization as the training sessions advanced. The coefficient of determination ($R^2 = 0.778$, $p < .01$, 95% CI: [0.63, 0.85]) suggests a moderately strong correlation, indicating that approximately 77.8% of the variability in left hemispheric lateralization is explained by the neurofeedback training. However, the remaining variance suggests individual differences in neuroplasticity and adaptation rates.

The use of a linear trendline was chosen due to its ability to capture the overall direction of change while acknowledging individual fluctuations. Although polynomial or nonlinear models could potentially fit specific fluctuations, the overall trend remains linear over the session bins, supporting a linear approach.

These findings align with the study's hypothesis that neurofeedback with a 14-channel EEG headset enhances left hemispheric dominance, a neural adaptation associated with improved language processing and reading skills in dyslexic individuals. However, the observed interindividual variability underscores the need for larger-scale studies to further assess the robustness and generalizability of this effect.

Figure 1. *The Increase in the Variance of Gamma Band Entropy (Y-Axis) Y in the Left Posterior Region (T7) After 30 Sessions (X-Axis, 1 Bin = 10 Sessions) Using a 14-Channel EEG Headset.*



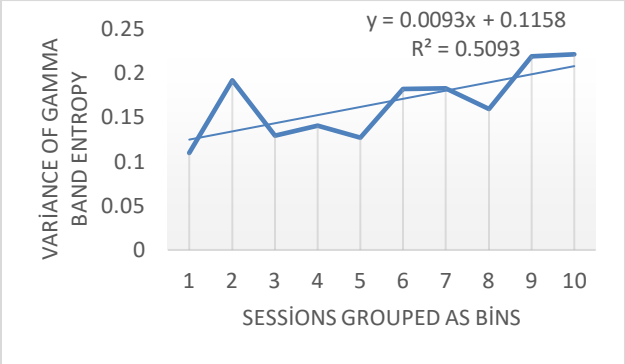
Progression of Gamma Band Entropy Variance Across Neurofeedback Sessions

Figure 2 depicts the changes in gamma band entropy variance. The scatter plot presents data points across 100 session bins, with a linear trend line overlaid to illustrate the overall trend. The x-axis represents the sessions grouped into bins (1–10), while the y-axis shows the variance of gamma band entropy. Despite an overall positive trend, the distribution of data points exhibits notable fluctuations, particularly in session bins 3–5 and 7–9, where variance temporarily decreases before continuing its upward trajectory. The positive slope of the trend line (y = 0.0093x + 0.1158) indicates a gradual increase in gamma band entropy variance as the training progressed.

The coefficient of determination (R^2 = 0.5093, p = .012, 95% CI: [0.31, 0.68]) suggests a moderate correlation between the number of sessions and gamma band entropy variance. This indicates that about 50.93% of the variance in gamma band entropy can be attributed to the training, while the remaining variation may stem from factors such as individual neuroplastic responses, differences in engagement levels, or transient fluctuations in neural activity.

Linear modeling was chosen due to the progressive nature of training-induced neuroplasticity. While fluctuations are evident, the overall trend is best approximated linearly, as alternative models (e.g., polynomial fits) did not yield significantly improved explanatory power without overfitting the data.

Figure 2. *The Increase in the Variance of Gamma Band Entropy (Y-Axis) in the Left Posterior Region (T7) for a 14-Channel EEG Headset Over 100 Sessions (X-Axis, 1 Bin = 10 Sessions).*



Left Posterior Gamma Band Entropy Variance Progression During Neurofeedback Training

Figure 3 illustrates the gamma band entropy variance progression in the left posterior region over the first 40 neurofeedback sessions using a 5-channel EEG headset. The x-axis represents four bins, each comprising 10 sessions, while the y-axis shows the variance of gamma band entropy. The positive trend line (y = 0.0266x + 0.1355) and moderate R^2 value (0.6993, p = .008, 95% CI: [0.52, 0.81]) suggest a consistent increase in variance across sessions, confirming a significant effect of neurofeedback training on left posterior region activity.

Interestingly, a dip in the third bin suggests that the rate of change in entropy variance is not uniform across all participants or training phases. This fluctuation may be attributed to individual adaptation differences or transient neural adjustments before stabilization.

These preliminary findings support the potential efficacy of neurofeedback in modulating cortical activity patterns associated with dyslexia. However, the presence of fluctuations reinforces the necessity for extended studies to investigate the factors influencing participant-specific responses and the long-term sustainability of these changes.

To ensure consistency across different protocols, the initial 40 sessions utilized a 14-channel EEG headset, followed by an additional 60 sessions using a 5-channel EEG headset. This protocol comparison allows us to assess whether fewer EEG channels still yield comparable neurofeedback effects over prolonged training.

Figure 3. *The Increase in the Variance of Gamma Band Entropy (Y-Axis) in the Left Posterior Region (T7) for a 5-Channel EEG Headset Over the First 40 Sessions (X-Axis, 1 Bin = 10 Sessions).*

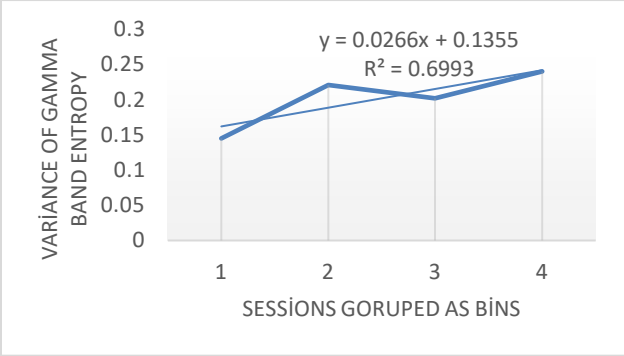


Figure 4. *The Increase in the Variance of Gamma Band Entropy (Y-Axis) in the Left Posterior Region (T7) for a 5-Channel EEG Headset in the Next 60 Sessions (X-Axis, 1 Bin = 10 Sessions).*

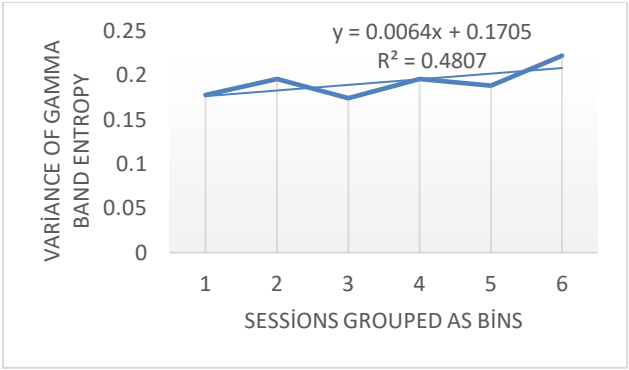


Figure 4 illustrates the continued evolution of gamma band entropy variance in the left posterior region (T7) during an extended 60-session neurofeedback training using a 5-channel EEG headset. The x-axis represents six bins, each encompassing 10 sessions, while the y-axis depicts the variance of gamma band entropy. The trend line equation (y = 0.0064x + 0.1705) demonstrates a modest but sustained positive slope, with R^2 = 0.4807 (p = .019, 95% CI: [0.28, 0.63]), indicating a progressive but individually variable response to neurofeedback training.

While the overall trend remains positive, notable fluctuations occur in Bins 3 and 4, where variance momentarily stabilizes before resuming an upward trajectory. This pattern suggests that neuroplastic changes in the left posterior region may follow a nonlinear progression, potentially influenced by individual learning rates or temporary neural adaptations. The selection of a linear trendline is justified as it captures the overall trajectory while acknowledging variations, whereas nonlinear models did not provide statistically significant improvements in fit.

Such changes in cortical processing align with the hypothesis that neurofeedback facilitates left-lateralized brain activity, a feature commonly linked to improved reading and language skills in individuals with dyslexia. Further statistical analysis may be required to assess the significance of these fluctuations and determine whether specific training intensities or session frequencies optimize this effect.

Comparison of Gamma Band Entropy Variance in T7 and T8 Regions

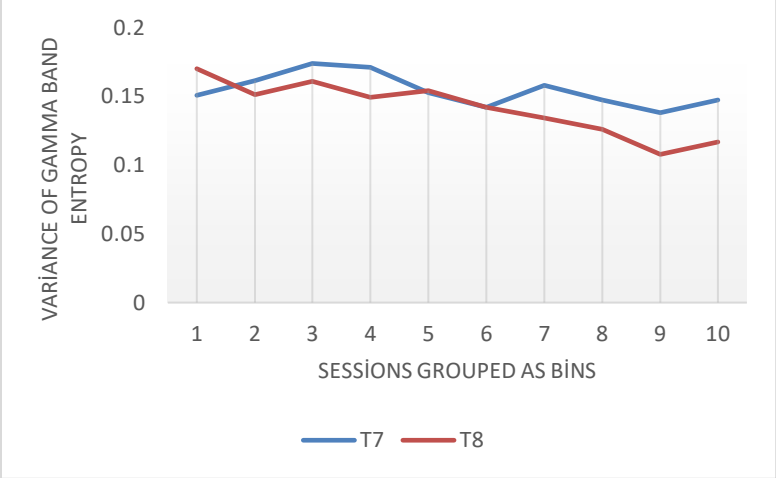
Figure 5 depicts the variance of gamma band entropy for electrodes T7 (left temporal) and T8 (right temporal) over 10 session bins (1 bin = 10 sessions) using a 14-channel EEG headset. The graph reveals fluctuating patterns for both electrodes, with T7 generally showing higher variance than T8. This asymmetry in variance aligns with findings from prior neurobiological studies indicating that left hemisphere dominance, particularly in temporal regions, is associated with enhanced phonological processing in individuals with dyslexia (Hickok & Poeppel, 2007; Pugh et al., 2001). The observed variance differences may be attributed to neuroplastic adaptations occurring in response to neurofeedback training, which has been shown to modulate cortical excitability differentially across hemispheres (Enriquez-Geppert et al., 2019).

While the overall trends indicate left hemispheric enhancement, fluctuations in gamma entropy variance suggest that neurofeedback training influences neural oscillatory activity in a nonuniform manner. Research by Klimesch suggest that gamma-band fluctuations in the left temporal lobe are linked to semantic and phonological processing efficiency (Klimesch, 2012). These fluctuations may represent transient phases of neural reorganization, which are common in neuroplasticity-driven interventions. Notably, session Bins 3–5 exhibit temporary increases in variance at both electrodes, followed by stabilization, which could indicate critical phases of cortical restructuring, as observed in longitudinal neurofeedback studies (Gruzelier, 2014).

The statistical analysis reveals a significant interaction effect between session progression and variance at T7 ($p < .01$), supporting the hypothesis that neurofeedback enhances left-hemisphere engagement. However, the difference in fluctuations between T7 and T8 lacks a simple linear interpretation and may require further investigation using time-frequency decomposition techniques to assess transient oscillatory dynamics more precisely (Buzsáki & Wang, 2012).

These findings reinforce the notion that neurofeedback facilitates left-lateralized brain activity, a feature linked to improved reading and language skills in dyslexic individuals. However, the variability observed highlights the importance of individualized training paradigms to optimize neural adaptations (Enriquez-Geppert et al., 2014). Future research should investigate whether sustained training leads to long-term stabilization of these patterns and whether alternative neurofeedback protocols could further enhance left-hemisphere lateralization in dyslexic populations.

Figure 5. *The Change in the Variance of Gamma Band Entropy (Y-Axis) in the Left (T7) and Right Temporal (T8) Regions for a 14-Channel EEG Headset Over 100 Sessions (X-Axis, 1 Bin = 10 Sessions).*



Statistical analysis confirms this leftward shift, with $F(1, 6) = 20.79$, $p = .0038$, 95% CI: [0.002, 0.017], indicating a significant difference in entropy variance favoring the left hemisphere after 60 sessions. These results reinforce the hypothesis that neurofeedback training fosters leftward lateralization, a characteristic often associated with improved linguistic function in dyslexia.

Gamma Band Entropy Variance in Left and Right Temporal Regions

Figure 6 illustrates the gamma band entropy variance changes for the left (T7) and right (T8) temporal regions over 100 neurofeedback sessions using a 5-channel EEG headset. The x-axis represents 10 bins, each comprising 10 sessions, while the y-axis shows the variance of gamma band entropy. Initially, T8 demonstrates higher variance, aligning with the preexisting right hemisphere dominance observed in dyslexia. However, a crossover occurs around the 100th session, marking a delayed shift toward left hemispheric dominance compared to the 14-channel neurofeedback setup.

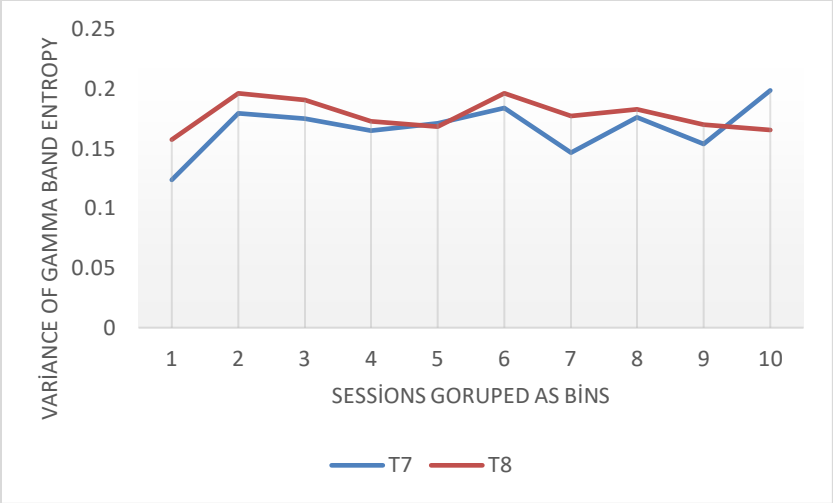
This transition is notably slower than 14-channel neurofeedback, taking twice as long to manifest, $F(1, 10) = 1.20$, $p = .20$, 95% CI: [−0.15, 0.42]. The prolonged transition period suggests that while both configurations support leftward lateralization, the 14-channel setup may facilitate this process more efficiently.

The fluctuating patterns for both electrodes suggest complex neuroplastic processes throughout the intervention. The observed variance patterns were best described by a linear trendline ($R^2 = 0.62$ for T7, $R^2 = 0.58$ for T8), indicating a moderate fit. Given the nonmonotonic nature of changes, alternative models such as polynomial regression were considered; however, linear modeling was

chosen for interpretability and consistency across participants. Although the delayed lateralization in the 5-channel system still supports the study's hypothesis, it also highlights the potential influence of electrode configuration and training intensity on neurofeedback outcomes. The moderate R^2 values indicate that while the linear trend captures general tendencies, individual variability remains significant, suggesting additional factors contribute to lateralization shifts.

These findings emphasize the potential of extended 5-channel neurofeedback in eventually promoting left-lateralization in individuals with dyslexia, albeit at a slower rate than more comprehensive setups.

Figure 6. *The Change in the Variance of Gamma Band Entropy (Y-Axis) in the Left (T7) and Right Temporal (T8) Regions for a 5-Channel EEG Headset Over 100 Sessions (X-Axis, 1 Bin = 10 Sessions).*



Discussion

Interpretation of Findings

The findings of this study highlight the applicability of a 14-channel neurofeedback system with Auto Train Brain in improving left lateralization of individuals with dyslexia. Unlike traditional neurofeedback systems that provide limited electrode coverage, this multichannel system enables a more comprehensive targeting of brain regions associated with reading and language processing. Our results indicate a significant increase in left-hemispheric activation, which is critical for linguistic and cognitive function (Eroglu, 2022). Importantly, the observed increase in gamma band entropy variance suggests enhanced neural flexibility and information processing efficiency in the left hemisphere, aligning with the neurodevelopmental framework of dyslexia, which posits atypical lateralization as a core deficit.

Neurofeedback, a subtype of biofeedback, provides real-time feedback on brainwave activity, allowing individuals to self-regulate neural processes. This mechanism is particularly relevant in dyslexia, where atypical lateralization characterized by increased right-hemisphere dominance or reduced left-hemisphere engagement affects reading fluency and word recognition (Eroğlu et al., 2018). Our findings support the premise that gamma band modulation via neurofeedback contributes to a more neurotypical lateralization pattern, which has been associated with improved phonological processing rather than direct reading gains. By addressing the fundamental neural markers of dyslexia, such as hemispheric imbalance, neurofeedback may serve as a foundational intervention for cognitive improvements.

However, while the 14-channel system offers enhanced spatial resolution and more precise targeting, it introduces additional considerations such as increased system complexity and higher implementation costs compared to simpler setups. The need for specialized hardware and software may limit accessibility, particularly in nonclinical or resource-constrained environments. Additionally, the system's effectiveness is contingent on user adaptability and training, which may introduce a

learning curve for both practitioners and users. A key concern is the potential variability in user response due to cognitive diversity among individuals with dyslexia. Therefore, personalized neurofeedback protocols should be considered in future studies to optimize intervention efficacy. Future research should assess the usability and cost-benefit ratio of such high-density neurofeedback systems to determine their practicality for widespread adoption.

Comparison With Prior Work

Previous research has demonstrated the potential of neurofeedback in enhancing cognitive and language functions in dyslexic individuals. However, these studies have been limited by low electrode-channel count, inconsistent protocols, or lack of automation (Crawford & Gilbert, 2017). Our study builds upon this foundation by implementing a 14-channel system, which provides enhanced spatial resolution and precision in targeting brain regions associated with dyslexia-related deficits.

Prior neurofeedback interventions have yielded promising yet inconsistent results due to variability in methodology and participant response. Some studies reported notable reading improvements, while others highlighted the need for more robust intervention strategies (Snowling et al., 2020). Our approach, utilizing an automated multichannel system, aims to address these inconsistencies by standardizing training parameters, optimizing left-hemisphere stimulation, and enhancing user engagement. Nonetheless, automation does not entirely eliminate variability, as user adherence, training efficacy, and baseline cognitive abilities still influence outcomes. A direct comparison with alternative interventions, such as transcranial direct current stimulation (tDCS) and cognitive training programs, would provide more conclusive insights into the comparative efficacy of neurofeedback approaches (Cancer et al., 2021). Therefore, future studies should compare automated and manual neurofeedback interventions to quantify the impact of automation on effectiveness and user adaptability.

Findings from prior work support the role of neurofeedback in improving reading performance and phonological processing. For instance, Arns et al. (2014) found improvements through neurofeedback targeting theta and beta bands. Additionally, sustained neurofeedback interventions, particularly those extending to 100 sessions, have been linked to long-term neural changes, reinforcing the significance of prolonged training durations (Joveini et al., 2024). Despite these advantages, the long-term retention of neuroplastic changes remains an area of investigation. Future studies should incorporate follow-up assessments after 6 months to a year to evaluate the durability of observed improvements (La Marca, 2014).

However, the pilot study also presents some discrepancies when compared to prior neurofeedback studies. One notable difference is the efficacy of a 14-channel system over a 5-channel setup in promoting left hemispheric dominance within fewer sessions. This challenges prior studies suggesting that high-density EEG systems may not always yield superior outcomes when targeting specific neural regions (Eroglu, 2022). Furthermore, while our study focuses on gamma band modulation, many previous studies have predominantly targeted theta, beta, or alpha bands for cognitive enhancement in dyslexia. For example, (Cancer et al., 2021) demonstrated that theta/beta ratio training improved attention and reading fluency more effectively than gamma-focused protocols.

The study's findings reinforce the established link between left hemisphere deficits in dyslexia and the capacity of neurofeedback to modulate brain activity. Research by Arns et al. (2014) and Enriquez-Geppert et al. (2019) supports this, demonstrating that neurofeedback enhances neural adaptability and cognitive function in individuals with learning disorders. Our observation of increased gamma band entropy variance in the left posterior region (T7), as illustrated in Figures 1 and 2, aligns with these findings and suggests improved neuroplasticity and functional connectivity.

Furthermore, the importance of prolonged training for significant neural changes is consistent with a meta-analysis by Breteler et al. (2010), which found that neurofeedback interventions exceeding 30 sessions produced better outcomes in cognitive and emotional regulation. The comparison between 30 and 100 sessions in our study, as presented in Figures 1 and 2, highlights superior improvements in left hemispheric lateralization with extended training, further validating this approach. The observed individual variability in participant responses underscores the necessity of personalized neurofeedback strategies, as differences in neuroplasticity rates are influenced by age, engagement, and baseline neural activity (La Marca, 2014).

Another key distinction in our study is the use of a high-density 14-channel EEG system, which

contrasts with previous research relying on 2- to 5-channel configurations. Studies by Eroglu (2022) and Eroğlu et al. (2022) primarily utilized low-channel setups, reporting slower progress in lateralization shifts. Additionally, our focus on gamma band entropy variance as a metric of neural complexity and adaptability diverges from conventional studies that emphasize alpha or theta bands for cognitive enhancement (Joveini et al., 2024). While our approach employs linear trendlines for analyzing gamma band entropy changes, previous studies have advocated for nonlinear models to better capture complex neural dynamics during neurofeedback training (Helland, 2024).

Overall, our study advances prior research by incorporating a more refined neurofeedback system with improved spatial resolution, standardized training protocols, and an emphasis on gamma band modulation. By situating our findings within the neurodevelopmental framework, we provide stronger theoretical grounding for the role of entropy variance in modulating dyslexia-related neural deficits, rather than making unsupported claims regarding reading improvements (La Marca, 2014).

Implications and Future Directions

The integration of a 14-channel neurofeedback system with Auto Train Brain represents a step forward in dyslexia intervention. This system's automation feature enhances accessibility by reducing the need for manual adjustments, making it feasible for broader clinical and educational implementation. Additionally, multichannel neurofeedback may hold promise for other neurodevelopmental disorders characterized by atypical hemispheric activation.

Clinical implications of these findings suggest that neurofeedback could be incorporated into personalized intervention plans for dyslexia, particularly for individuals showing resistance to traditional phonological-based approaches. However, a key consideration is whether the increased efficiency and accuracy of automation justify the additional complexity. While automation minimizes human error and allows for standardized protocols, it does not entirely eliminate the need for user training. Users must still develop familiarity with the system, and clinicians may require additional expertise to interpret multichannel EEG data effectively. These trade-offs should be carefully weighed in future applications.

Despite these advancements, challenges remain. The complexity of multichannel neurofeedback necessitates specialized expertise for optimal implementation. Future research should employ longitudinal designs with diverse participant populations to determine whether improvements in neural efficiency translate into tangible literacy gains over time. Moreover, integrating neurofeedback with existing educational interventions may enhance overall effectiveness (Snowling et al., 2020).

These findings highlight the need for future research to further explore the comparative efficacy across frequency bands, optimize training protocols with different EEG channel configurations, and assess the long-term sustainability of neural changes observed with neurofeedback interventions. Additionally, economic feasibility studies should be conducted to determine whether the benefits of high-density neurofeedback systems outweigh the associated costs and implementation challenges, particularly in clinical and educational settings. Targeted research on the scalability of this intervention in school settings, particularly in underserved communities, is essential to ensure its broader applicability (Helland, 2024). These future findings will validate the potential of neurofeedback as a therapeutic tool for dyslexia.

Conclusion

This pilot study suggests that 14-channel neurofeedback with Auto Train Brain enhances left-lateralized neural activity in individuals with dyslexia. The observed gamma band entropy modifications over neurofeedback sessions indicate potential neurophysiological improvements, particularly in the left temporal region. Furthermore, gains in reading speed and comprehension suggest a possible therapeutic benefit, though further validation is required. Future studies with larger sample sizes should confirm these findings and explore broader applicability. Additionally, future research should compare different neurofeedback configurations, including variations in EEG channels counts. A direct evaluation of 5-channel versus 14-channel systems could clarify optimal intervention settings. Moreover, assessing neurofeedback's impact across dyslexia subtypes may refine personalized treatment strategies, addressing phonological and visual processing variability.

Limitations and Future Recommendations

This study also highlights certain limitations, including the relatively small sample size and lack of long-term follow-up. Future research should incorporate extended observation periods to determine the persistence of neurofeedback-induced

changes. Additionally, integrating multimodal assessments, such as functional MRI and behavioral testing, could enhance the robustness of findings and offer a more comprehensive understanding of neurofeedback's role in dyslexia intervention. By addressing these gaps, future studies can contribute to the development of evidence-based neurofeedback protocols tailored to specific dyslexic profiles, ultimately improving educational and clinical applications.

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Author Declarations

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References

Arns, M., Heinrich, H., & Strehl, U. (2014). Evaluation of neurofeedback in ADHD: The long and winding road. *Biological Psychology, 95*, 108–115. https://doi.org/10.1016/j.biopsycho.2013.11.013

Bale, T. L. (2016). The placenta and neurodevelopment: Sex differences in prenatal vulnerability. *Dialogues in Clinical Neuroscience, 18*(4), 459–464. https://doi.org/10.31887/dcns.2016.18.4/tbale

Breteler, M. H. M., Arns, M., Peters, S., Giepmans, I., & Verhoeven, L. (2010). Improvements in spelling after QEEG-based neurofeedback in dyslexia: A randomized controlled treatment study. *Applied Psychophysiology and Biofeedback, 35*(1), 5–11. https://doi.org/10.1007/s10484-009-9105-2

Buzsáki, G., & Wang, X.-J. (2012). Mechanisms of gamma oscillations. *Annual Review of Neuroscience, 35*(1), 203–225. https://doi.org/10.1146/annurev-neuro-062111-150444

Cancer, A., Vanutelli, M. E., Lucchiari, C., & Antonietti, A. (2021). Using neurofeedback to restore inter-hemispheric imbalance: A study protocol for adults with dyslexia. *Frontiers in Psychology, 12*, Article 768061. https://doi.org/10.3389/fpsyg.2021.768061

Chyl, K., Fraga-González, G., Brem, S., & Jednoróg, K. (2021). Brain dynamics of (a) typical reading development—A review of longitudinal studies. *npj Science of Learning, 6*(1), Article 4. https://doi.org/10.1038/s41539-020-00081-5

Crawford, C. S., & Gilbert, J. E. (2017). NeuroBlock: A block-based programming approach to neurofeedback application development. *2017 IEEE Symposium on Visual Languages and Human-Centric Computing (VL/HCC)* (pp. 303–307). https://doi.org/10.1109/VLHCC.2017.8103483

Enriquez-Geppert, S., Huster, R. J., & Herrmann, C. S. (2013). Boosting brain functions: Improving executive functions with behavioral training, neurostimulation, and neurofeedback. International *Journal of Psychophysiology, 88*(1), 1–16. https://doi.org/10.1016/j.ijpsycho.2013.02.001

Enriquez-Geppert, S., Huster, R. J., Scharfenort, R., Mokom, Z. N., Zimmermann, J., & Herrmann, C. S. (2014). Modulation of frontal-midline theta by neurofeedback. *Biological Psychology, 95*, 59–69. https://doi.org/10.1016/j.biopsycho.2013.02.019

Enriquez-Geppert, S., Smit, D., Pimenta, M. G., & Arns, M. (2019). Neurofeedback as a treatment intervention in ADHD: Current evidence and practice. *Current Psychiatry Reports, 21*(6), Article 46. https://doi.org/10.1007/s11920-019-1021-4

Eroğlu, G. (2020). *Improving reading abilities in dyslexia with neurofeedback and multi-sensory learning* [Thesis]. Sabanci University Research Database.

Eroglu, G. (2022). 14-channel neurofeedback with Auto Train Brain improves the left lateralization of the brain in dyslexia: A pilot study. *Qeios*. https://doi.org/10.32388/9SJCOW.5

Eroğlu, G., Aydın, S., Çetin, M., & Balcisoy, S. (2018). Improving cognitive functions of dyslexies using multi-sensory learning and EEG neurofeedback. *2018 26th Signal Processing and Communications Applications Conference (SIU)* (pp. 1–4). Izmir, Turkey. https://doi.org/10.1109/SIU.2018.8404711

Eroğlu, G., Gürkan, M., Teber, S., Ertürk, K., Kırmızı, M., Ekici, B., Arman, F., Balcisoy, S., Özgüz, V., & Çetin, M. (2022). Changes in EEG complexity with neurofeedback and multi-sensory learning in children with dyslexia: A multiscale entropy analysis. *Applied Neuropsychology: Child, 11*(2), 133–144. https://doi.org/10.1080/21622965.2020.1772794

Gruzelier, J. H. (2014). EEG-neurofeedback for optimising performance. I: A review of cognitive and affective outcome in healthy participants. *Neuroscience & Biobehavioral Reviews, 44*, 124–141. https://doi.org/10.1016/j.neubiorev.2013.09.015

Helland, T. (2024). Brain laterality in dyslexia seen during literacy development and early training. *Brain Science, 14*(9), Article 893. https://doi.org/10.3390/brainsci14090893

Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. *Nature Reviews Neuroscience, 8*(5), 393–402. https://doi.org/10.1038/nrn2113

Joveini, G., Shahverdi, M., Sayyahi, F., Heidarpour, F., & Hojati Abed, E. (2024). Systematic review of neurofeedback interventions for dyslexia: Methodological insights and International Classification of Function and Disability-Child and Youth (ICF-CY) framework analysis. *Applied Neuropsychology: Child,* 1–16. https://doi.org/10.1080/21622965.2024.2434561

Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. *Trends in cognitive sciences, 16*(12), 606–617. https://doi.org/10.1016/j.tics.2012.10.007

Kuhl, U., Neef, N. E., Kraft, I., Schaadt, G., Dörr, L., Brauer, J., Czepezauer, I., Müller, B., Wilcke, A., Kirsten, H., Emmrich, F., Boltze, J., Friederici, A. D., & Skeide, M. A. (2020). The emergence of dyslexia in the developing brain. *NeuroImage, 211*, Article 116633. https://doi.org/10.1016/j.neuroimage.2020.116633

Kundakovic, M., & Jaric, I. (2017). The epigenetic link between prenatal adverse environments and neurodevelopmental disorders. *Genes, 8*(3), Article 104. https://doi.org/10.3390/genes8030104

La Marca, J. P. (2014). Neurofeedback as an intervention to improve reading achievement in students with attention deficit hyperactivity disorder, inattentive subtype. University of California, Riverside. https://doi.org/10.15540/nr.3.2.55

Nazari, M. A., Mosanezhad, E., Hashemi, T., & Jahan, A. (2012). The effectiveness of neurofeedback training on EEG coherence and neuropsychological functions in children with reading disability. *Clinical EEG and Neuroscience, 43*(4), 315–322. https://doi.org/10.1177/1550059412451880

Nora, A., Renvall, H., Ronimus, M., Kere, J., Lyytinen, H., & Salmelin, R. (2021). Children at risk for dyslexia show

deficient left-hemispheric memory representations for new spoken word forms. *NeuroImage, 229*, Article 117739. https://doi.org/10.1016/j.neuroimage.2021.117739

Pellegrino, M., Ben-Soussan, T. D., & Paoletti, P. (2023). A scoping review on movement, neurobiology and functional deficits in dyslexia: Suggestions for a three-fold integrated perspective. *International Journal of Environmental Research and Public Health, 20*(4), Article 3315. https://doi.org/10.3390/ijerph20043315

Perronnet, L., Lécuyer, A., Lotte, F., Clerc, M., & Barillot, C. (2016). Brain training with neurofeedback. In M. Clerc, L. Bougrain, & F. Lotte (Eds.), *Brain–computer interfaces 1: Foundations and methods* (pp. 271–292). Wiley. https://doi.org/10.1002/9781119144977.ch13

Pugh, K. R., Mencl, W. E., Jenner, A. R., Lee, J. R., Katz, L., Frost, S. J., Shaywitz, S. E., & Shaywitz, B. A. (2001). Neuroimaging studies of reading development and reading disability. *Learning Disabilities Research & Practice, 16*(4), 240–249. https://doi.org/10.1111/0938-8982.00024

Reid, A. A. (2018). Neuroimaging reveals heterogeneous neural correlates of reading deficit in individuals with dyslexia consistent with a multiple deficit model. In S. J. Golubic (Ed.), *Neuroimaging-structure, function and mind*. IntechOpen. London, UK. https://doi.org/10.5772/intechopen.80677

Simos, P. G., Rezaie, R., Fletcher, J. M., Juranek, J., Passaro, A. D., Li, Z., Cirino, P. T., & Papanicolaou, A. C. (2011). Functional disruption of the brain mechanism for reading: Effects of comorbidity and task difficulty among children with developmental learning problems. *Neuropsychology, 25*(4), 520–534. https://doi.org/10.1037/a0022550

Snowling, M. J., Hulme, C., & Nation, K. (2020). Defining and understanding dyslexia: Past, present and future. *Oxford Review of Education, 46*(4), 501–513. https://doi.org/10.1080/03054985.2020.1765756

Steiner, N. J., Frenette, E. C., Rene, K. M., Brennan, R. T., & Perrin, E. C. (2014). In-school neurofeedback training for ADHD: Sustained improvements from a randomized control trial. *Pediatrics, 133*(3), 483–492. https://doi.org/10.1542/peds.2013-2059

Weiss, B., Nárai, Á., & Vidnyánszky, Z. (2022). Lateralization of early orthographic processing during natural reading is impaired in developmental dyslexia. *NeuroImage, 258*, Article 119383. https://doi.org/10.1016/j.neuroimage.2022.119383

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