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On the Effects of Non-Invasive Brain Stimulation Techniques on Developmental Dyslexia: A Systematic Review of Randomized Controlled Trials

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Abstract

Objective: Non-invasive brain stimulation (NIBS) can safely influence brain activity, enhancing cognitive functions and offering potential benefits for learning disabilities like dyslexia. This paper aims to fill the current gap in comprehensive reviews on NIBS studies specifically targeting dyslexic individuals.
Method: we conducted a systematic review across several databases, including PubMed, Web of Science, Scopus, Google Scholar, and CENTRAL Cochrane. The initial search strategy was designed to be as comprehensive as possible to capture all pertinent studies. We did not impose any language restrictions or time constraints during our search. The strategy was initially created using MEDLINE MeSH terms and subsequently adapted for the other databases. Our search included the keywords "dyslexia" in combination with "NIBS", "transcranial magnetic stimulation (TMS)", "transcranial direct current stimulation (tDCS)", and other NIBS types like repetitive TMS and transcranial alternating current stimulation (tACS).
Results: 17 randomized controlled trial (RCT) studies were found to meet the eligibility criteria and are included in this review. Findings showed that repeated tDCS sessions, when paired with reading interventions, can effectively enhance reading abilities. Studies indicate that anodal tDCS applied to the left temporo-parietal cortex (TPC) and cathodal tDCS to the right TPC, along with phonology-based reading training, have led to improvements in various reading metrics, including the reading of pseudo-words and low-frequency words. Notably, traditional reading areas appear to respond well to modulation through NIBS, and facilitative protocols can enhance various subprocesses related to reading.
Conclusion: Research indicates that tDCS, when used with reading interventions, enhances specific reading skills in individuals with dyslexia. Additionally, gamma-tACS applied to the left auditory cortex yields short-term improvements in neurophysiological responses to auditory stimuli. However, further randomized controlled trials with long-term follow-ups are necessary to establish the clinical effectiveness of these interventions.

Key words: *Developmental Dyslexia; Magnetic Stimulation; Reading; Systematic Review; Transcranial Direct Current Stimulation (tDCS); Transcranial; Transcranial Electrical Stimulations*

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While reading and writing may seem instinctive, it's important to recognize these skills as significant cultural milestones (1). In contemporary societies, the ability to read and write is crucial for engaging in daily activities, professional life, and personal interactions. Effective communication through written language is a cornerstone of modern existence, positioning literacy as a vital component of education, employment opportunities, and a satisfying social life. Given the critical importance of these abilities, it is concerning that a notable number of children struggle to develop literacy skills even with adequate instruction. This group is often identified as having dyslexia (2). Dyslexia is one of the most prevalent learning disabilities, affecting approximately 5–10% of children of school age worldwide (3). Despite receiving proper educational resources and having typical cognitive abilities, children with dyslexia encounter significant challenges with literacy acquisition (4). The leading theory regarding the root causes of dyslexia is the phonological coding deficit hypothesis (5), which posits that individuals with dyslexia often struggle with decoding and recognizing phonological elements of spoken language and retrieving phonological information from memory (6, 7). More specifically, many dyslexics exhibit auditory and/or phonological deficits (8). For children at risk of dyslexia, it is crucial to monitor and assess pre-literacy skills, initiate early intervention strategies, and implement proactive prevention measures as soon as possible. Since indicators of potential dyslexia can be detected at the preschool level, early screening in pediatric settings is essential (9). Additionally, research indicates that dyslexia may contribute to emotional and behavioral challenges, mental health concerns (such as anxiety and conduct disorders), and higher rates of unemployment in adulthood (10), highlighting the urgent need for supportive measures.

In recent decades, numerous studies have investigated brain activation patterns associated with literacy development in both typically developing readers and those with disabilities (11-13). Research has found that reading is predominantly supported by three interconnected and largely universal neural circuits: the left inferior frontal cortex (linked to the storage and sequencing of phonetic information), the left dorsal temporo-parietal cortex (TPC, which is believed to function as the center for grapheme-phoneme conversion), and the left ventral occipito-temporal cortex (VOTC, likely specialized for the orthographic processing of written language) (14, 15). Additionally, a review (16) highlights the significance of other linguistic regions beyond the traditional reading areas, such as the left posterior parietal cortex and the anterior temporal lobe, which play important roles in the various subprocesses involved in reading. Neuroimaging research also indicates that both children and adults with dyslexia demonstrate notably reduced activation in key reading areas during tasks related to reading, such as phoneme elision, lexical decision-making, and reading aloud (17). Studies have confirmed these functional activation discrepancies in at-risk children (18), children with reading impairments (19) and adults (20), with some variation noted across different age groups. Specifically, at-risk children typically exhibit underactivation, primarily in the left TPC and, to a lesser extent, in the VOTC and cerebellum. In contrast, children with reading disabilities show significantly lower activation levels in the left inferior frontal regions as well.

Various behavioral interventions are currently being implemented and evaluated with the aim of boosting reading skills in the affected and at-risk youth (21, 22). Behavioral interventions for dyslexia and reading impairments typically focus on structured approaches to improve literacy skills through specific strategies such as phonics training, reading comprehension exercises, and multi-sensory learning techniques (23, 24). These interventions aim to enhance reading abilities by strengthening cognitive processes related to language and reading. However, despite their widespread use and some demonstrated effectiveness, these methods have limitations. They often require significant time and resources, and the outcomes can vary widely among individuals. Moreover, while behavioral interventions can support skill development, they may not address the underlying neurological factors associated with dyslexia, potentially leading to incomplete success in fostering long-term reading proficiency (25). As a result, practitioners advocate for a combination of behavioral approaches alongside neurobiological assessments to better target therapy and support needs. In contrast to advancements in behavioral therapies, there has been limited exploration into whether neural modulations might be equally or more effective. Consequently, there is a pressing need to investigate the potential of neurostimulation techniques within the reading network for children and adolescents facing challenges in reading and writing (26), yet research in this area remains sparse.

Noninvasive brain stimulation (NIBS) techniques, such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS), are emerging as promising interventions for individuals with dyslexia. Given the encouraging outcomes of NIBS in various clinical groups, including individuals with depression (27, 28), risky behaviors (29-32), autism (33), and aphasia (34), NIBS may also represent a potential new treatment for learning disabilities. These methods aim to enhance neural activity in targeted brain regions associated with reading and language processing. TMS operates by delivering short bursts of high-current pulses through a magnetic coil, generating a strong magnetic field. This field induces electrical currents in the underlying brain tissue, leading to the generation of action potentials in neuronal axons (35). The resulting action potentials facilitate the release of neurotransmitters at synaptic terminals, thereby modulating overall brain activity (36). On the other hand, tDCS is believed to influence the resting membrane potential of cortical neurons, which can either enhance or reduce the probability of spontaneous or task-related firing (37). This modulation can affect neuronal function and behavior, resulting in either improved or worsened task performance. Specifically, anodal tDCS is generally associated with increased brain activation, while cathodal tDCS is thought to lead to reduced activation in that region. These variations in brain activation are believed to associate with specific behavioral outcomes (38). Therefore, by modulating brain function, NIBS may help improve literacy skills in children and adults with dyslexia, particularly in areas where traditional therapies have had limited success (39). Current research is exploring the effectiveness of NIBS in facilitating phonological awareness and decoding abilities, with the goal of providing a novel approach to support literacy acquisition. As studies continue to expand, NIBS could play a significant role in personalized interventions for those struggling with dyslexia.

A systematic review in 2022 suggested that multiple sessions of reading training, when paired with various NIBS protocols, can lead to sustained improvements in reading abilities for both children and adults with dyslexia (40). This finding suggests interesting possibilities for further investigation in this field. However, in addition to the limited database search conducted by this study, several clinical trials have been published in the last three years that could update our findings in this area. Therefore, the objective of this systematic review is to present a comprehensive synthesis of studies utilizing NIBS in individuals with dyslexia, enhancing our understanding of the neurobiological aspects of reading difficulties. Additionally, we seek to clarify the potential of NIBS as a therapeutic intervention by assessing various reading strategies implemented in these studies and examining their effectiveness and practicality. Lastly, we identify challenges encountered in this field and suggest directions for future research.

Materials and Methods

The search strategies employed for this review adhere to the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) guidelines. The criteria for study eligibility were based on specific characteristics: the studies with a randomized controlled trial (RCT) design utilized a NIBS protocol (single/multiple sessions) with either a between-subjects or within-subjects design, and participants were diagnosed with dyslexia in accordance with the regulations and criteria specific to their respective countries. Exclusion criteria were studies on participants with non-developmental dyslexia (e.g., post-stroke dyslexia and so on), studies on participants with other learning disorder, non-English papers, review articles, case reports and book chapters, lack of access to the full text of the article, and non-peer-reviewed papers .

Search Strategy

In order to assess the overall impact of NIBS techniques on dyslexia, we conducted a systematic review in December 2024 across several databases, including MEDLINE/PubMed, ISI Web of Science, Scopus, Google Scholar, and CENTRAL Cochrane. The initial search strategy was designed to be as comprehensive as possible to capture all pertinent studies. We did not impose any language restrictions or time constraints during our search. The strategy was initially created using MEDLINE MeSH terms and subsequently adapted for the other databases. Our search included the keywords “dyslexia” in combination with “NIBS”, “TMS”, “tDCS”, and other NIBS types like repetitive TMS and transcranial random noise stimulation (tRNS). Additional pertinent studies were also obtained from the reference lists of the selected articles.

Study Selection

Two authors independently reviewed the studies identified through the search and evaluated them against the eligibility criteria using the information provided in the titles and abstracts. They determined whether each study met the inclusion criteria. If there was uncertainty about excluding an article by consensus, the full text was obtained for further evaluation, as was done for any articles that were not outright rejected. In instances where they disagreed, a consensus decision was reached.

Quality Assessment

To facilitate the interpretation of findings and minimize bias in the review, two independent researchers evaluated the validity and quality of the chosen articles by employing the Consolidated Standards of Reporting Trials (CONSORT) checklist (41). They assessed various aspects related to the methodology, results, and discussion of each study. Each article was assigned an overall quality score, which contributed to the synthesis of data and the overall interpretation of the review's outcomes.

Data Extraction

Following the PRISMA guidelines, two separate researchers conducted the data extraction process, gathering pertinent information from each selected study. This included details such as the authorship, publication date, study design, participant count, average age, gender distribution, type of NIBS method used, stimulation parameters, targeted brain regions, various outcome measures, follow-up intervals, and any other relevant information.

Results

Our search queries produced a total of 63 records in PubMed, 150 records in ISI, 127 records in Scopus, and 0 records in Cochrane. Also, we screened the first 300 records of Google scholar due to limited relevance beyond that point. After removing 218 duplicates, 422 studies were totally evaluated against the inclusion criteria by examining their titles and abstracts, with the majority (389) being excluded based on these elements (Figure 1). A total of 33 studies were subjected to a more detailed evaluation because they satisfied initial inclusion requirements. Ultimately, 17 RCT studies were found to meet the eligibility criteria and are included in this review. Detailed information about the studies can be found in Table 1 and Table 2.

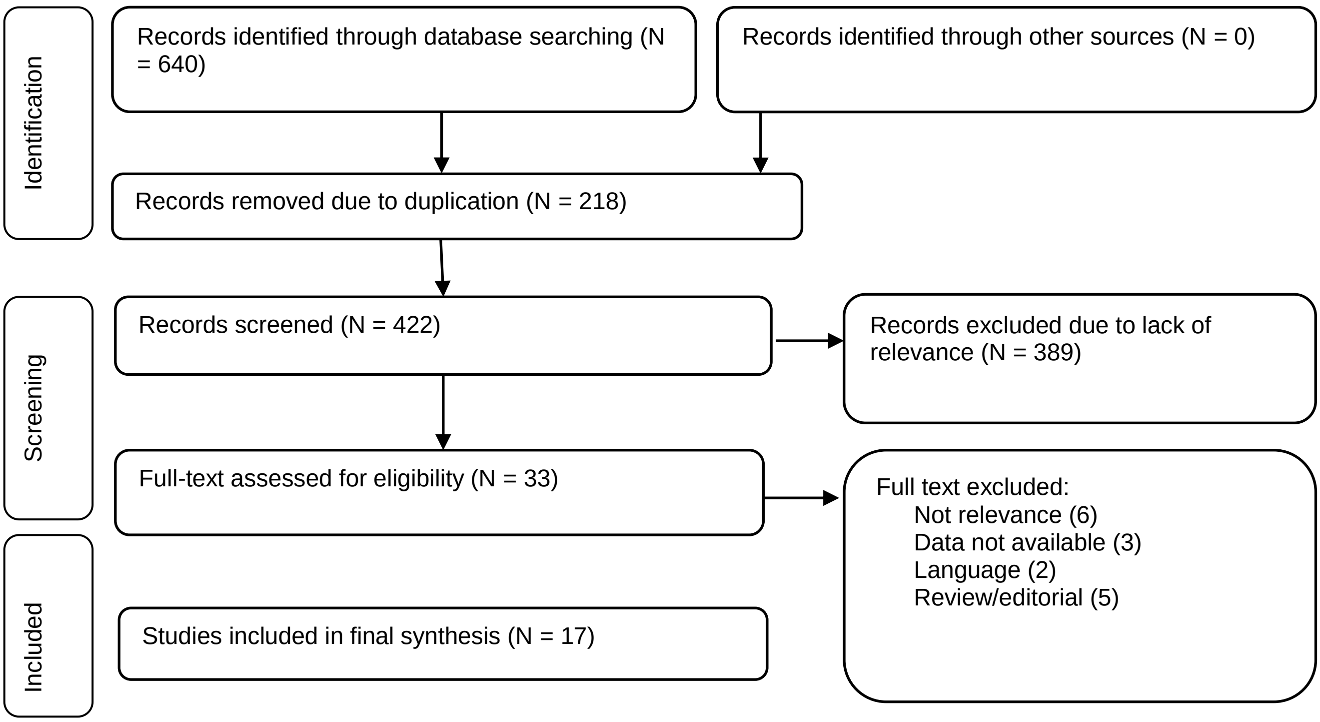

Figure 1. PRISMA Flowchart of Selected Studies on the Effects of Non-Invasive Brain Stimulation Techniques on Developmental Dyslexia.

Table 1. Study and Sample Characteristics for Included Studies on the Effects of Non-Invasive Brain Stimulation Techniques on Developmental Dyslexia.

Authors (year)	NIBS technique	Study	Design			N Intervention (mean age)	N Control (mean age)	Gender	Risk of Bias
			Randomization	Blinding	Control				
Rufener et al. (2023) (42)	tACS	Between-group RCT	Yes	Double blind	Sham	14 (11.85 ± 2.51)	15 (11.29 ± 2.37)	Both	Low
Mirahadi et al. (2023) (43)	tDCS	Between-group RCT	Yes	Double blind	Sham	14 (9.32 ± 1.90)	14 (8.86 ± 1.82)	Both	Low
Fazel et al. (2023) (44)	tDCS	Between-group RCT	Yes	No	Sham	20	20	Both	High
Rahimi et al. (2022) (45)	tDCS	Within-group RCT	Yes	Single blind	Sham	17 (10.35 ± 1.36)	17 (10.35 ± 1.36)	Both	Moderate
Werchowski et al. (2022) (46)	tACS	Between-group RCT	No	Double blind	Healthy control	13	22	Both	Moderate

Battisti et al. (2022) (47)	tDCS	Within-group RCT	Yes	Double blind	Sham	12 (12.42 ± 2.45)	12 (14.24 ± 2.68)	Both	Low
Lazzaro et al. (2021) (26)	tDCS	Between-group RCT	Yes	Double blind	Sham	13 (13.60 ± 2.40)	13 (13.90 ± 2.20)	Both	Low
Lazzaro et al. (2021) (48)	tDCS	Within-group RCT	No	Single blind	Sham	10 (13.89 ± 2.40)	10 (13.89 ± 2.40)	Both	High
Cummine et al. (2020) (49)	tDCS	Between-group RCT	Yes	Double blind	Sham	32 (22.20 ± 4.10)	28 (23.10 ± 4.40)	Both	Low
Marchesotti et al. (2020) (50)	tACS	Between-group RCT	No	Single blind	Sham (healthy control)	15 (27.40 ± 9.00)	15 (25.60 ± 7.80)	Both	High
Costanzo et al. (2019) (51)	tDCS	Between-group RCT	Yes	Double blind	Sham	13 (13.60 ± 2.40)	13 (13.90 ± 2.20)	Both	Low
Rahimi et al. (2019) (52)	tDCS	Within-group RCT	Yes	Single blind	Sham	17 (10.87 ± 1.30)	17 (10.87 ± 1.30)	Both	Moderate
Rufener et al. (2019) (53)	tACS and tRNS	Within-group study	Yes	Single blind	Sham	19 (13.30 ± 1.94); 15 (27.77 ± 7.64)	19 (13.30 ± 1.94); 15 (27.77 ± 7.64)	Both	Moderate
Costanzo et al. (2016) (54)	tDCS	Between-group RCT	Yes	Double blind	Sham	9 (12.56 ± 2.50)	9 (13.34 ± 2.12)	Both	Low
Costanzo et al. (2016) (55)	tDCS	Within-group RCT	Yes	Double blind	Sham	19 (13.70 ± 2.40)	19 (13.70 ± 2.40)	Both	Low
Heth et al. (2015) (56)	tDCS	Between-group RCT	Yes	No	Sham	10 (27.20 ± 7.20)	9 (24.50 ± 5.20)	Both	High
Costanzo et al. (2013) (57)	rTMS	Within-group RCT	Yes	Single blind	Sham	10 (35.80 ± 12.14)	10 (35.80 ± 12.14)	Both	Moderate

Twelve studies used tDCS (26, 43-45, 47-49, 51, 52, 54-56), four studies used tACS/tRNS (42, 46, 50, 53), and one study used rTMS to deliver transcranial stimulation to dyslexics (57). Ten studies had a between-subjects design and seven had a within-subjects design. About half of the studies (8/17) used a randomized double-blind sham controlled trial. Participants in all studies consisted of both male and female genders in different age ranges (from children to adults). Specifically, ten studies were conducted on children and adolescents (214 subjects), four studies were conducted on adults (119 subjects), one study was conducted on both children and adults (19 children and 15 adults), and two studies did not report the age of the participants (75 subjects). Regarding potential biases in the included articles, eight studies had a low risk of bias due to the double-blind sham-controlled design, five studies had a moderate risk of bias, and four studies had a high risk of bias. Six studies utilized a single-blind procedure leading to potential detection biases because the experimenter was not blinded to the stimulation condition. Werchowski *et al*. had no sham controls, which led to significant bias in the reported results (46). Most studies also suffer from a source of bias that may call their results into question, which is small sample sizes in the active and sham groups (less than 15 subjects). As shown in Table 2, five studies used concurrent phonemic training and NIBS and reported interesting results (26, 42, 43, 51, 54). However, this is another source of bias because appropriate control and experimental conditions were not considered in these studies for both interventions to assess the true effect of each intervention on the outcomes obtained alone. Five studies stimulated auditory cortex, six studies stimulated temporo-parietal cortex (TPC), one study stimulated prefrontal cortex, one study stimulated parieto-occipital cortex, one study stimulated SMG, and one study stimulated V5/MT. Furthermore, most studies used electrode size of 35 cm2, intensity of 1 mA, duration of 20 min, and bilateral montage for technical parameters of transcranial electrical stimulation techniques.

Table 2. Stimulation Parameters for Included Studies on the Effects of Non-Invasive Brain Stimulation Techniques on Developmental Dyslexia.

Authors (year)	Anode site (tDCS)/target electrode (tACS)	Cathode site (tDCS)/reference electrode (tACS)	Current (mA)	Frequency (Hz)	Electrode size (cm^2)	Duration (min)	Montage	Number of session	Concurrent reading training	Outcome measures	Results
Rufener (2023) (42)	T7 (left auditory cortex)	T8 (right auditory cortex)	1	40	35	20	Bilateral	10	Yes	Spelling and reading tests, short-term memory and phonemic discrimination	Improved phonemic processing and spelling skills in intervention group compared to sham
Mirahadi et al. (2023) (43)	Left TPC	Right TPC	2	-	35	20	Bilateral	15	Yes	Phonological and reading skills	Improved non-word reading and phonological awareness in intervention group compared to sham
Fazel et al. (2023) (44)	Not reported	Not reported	2	-	35	20	Not reported	20	No	Working memory and attention	Improved attention and working memory in intervention group compared to sham

Rahimi et al. (2022) (45)	T7 (left auditory cortex)	Right shoulder/ T8 (right auditory cortex)	1	-	25	20	Unilateral and bilateral	1	No	Auditory-verbal memory, auditory temporal processing, and reading skills	Improved pseudo-word reading and improved speed and accuracy of text reading in intervention groups compared to sham
Werchowski et al. (2022) (46)	Left prefrontal cortex	Right prefrontal cortex	1	12	35	20	Bilateral	1	No	Phonological decision	No significant tACS effect was observed
Battisti et al. (2022) (47)	PO7 (left parieto-occipital area)	PO8 (right parieto-occipital area)	1	-	35	20	Bilateral	5	No	Reading skills and neuro-psychological measures	Improved non-word reading speed in intervention group compared to sham
Lazzaro et al. (2021) (26)	Left TPC	Right TPC	1	-	25	20	Bilateral	18	Yes	Reading skill	Improved word reading fluency in intervention group compared to sham
Lazzaro et al. (2021) (48)	Left/right TPC	Left/right TPC	1	-	25	20	Bilateral	1	No	Reading skill	Left anodal and right cathodal TPC tDCS led to improved word recognition, reading accuracy, and motion perception
Cummine et al. (2020) (49)	P3 (left SMG)	Right shoulder	1.5	-	4	15	Unilateral	1	No	Reading skill	No significant tDCS effect was observed

Marchesotti et al. (2020) (50)	Left auditory cortex	Not reported	1.1 and 1.2	30 and 60	Not reported	20	Unilateral	1	No	Reading skill and phonemic awareness	30Hz-tACS led to improved reading accuracy and phonemic awareness compared to 60Hz-tACS and sham
Costanzo et al. (2019) (51)	Left TPC	Right TPC	1	-	25	20	Bilateral	18	Yes	Reading skill	Improved low-frequency word and pseudo-word reading in intervention group compared to sham
Rahimi et al. (2019) (52)	T7 (left auditory cortex)	Right shoulder/ T8 (right auditory cortex)	1	-	25	20	Unilateral and bilateral	1	No	ERP correlates and auditory processing	Improved visual attention processing in intervention group compared to sham
Rufener et al. (2019) (53)	T7 (left auditory cortex)	T8 (right auditory cortex)	1 for adolescents and 1.5 for adults	40 for tACS and (100-640) for tRNS	35	20	Bilateral	1	No	Voice onset discrimination	40Hz-tACS led to improved phoneme categorization in adolescents and adults. Moreover, tRNS led to improved phoneme categorization acuity in adults compared to sham
Costanzo et al. (2016) (54)	Left TPC	Right TPC	1	-	25	20	Bilateral	18	Yes	Reading skill	Improved reading speed and accuracy in intervention group compared to sham

Costanzo et al. (2016) (55)	Left/right TPC	Left/right TPC	1	-	25	20	Bilateral	1	No	Reading skill	Left anodal and right cathodal TPC tDCS led to improved reading accuracy compared to other groups
Heth et al. (2015) (56)	Left V5/MT	Right FP1	1.5	-	25 anode and 35 cathode	20	Unilateral	5	No	Reading skill	Improved reading fluency and speed in intervention group compared to sham
Costanzo et al. (2013) (57)	Coil placement: Left/right IPL/STG; Frequency: 5 Hz; 100% MT; Bilateral montage							1	No	Reading skill	Left STG stimulation led to improved reading accuracy and speed compared to other conditions

As expected, most studies assessed the core symptom of dyslexia, which is reading skills. However, some studies assessed subject's cognitive functions, including memory and attention. All tDCS studies, except Cummine *et al*. (49), have reported improvements in reading skills, including increased reading accuracy and speed, improved reading fluency, improved reading of pseudo-words and non-words, and low-frequency words in the active tDCS group compared to sham. Overall, 30 Hz and 40 Hz tACS and high frequency tRNS resulted in positive outcomes in dyslexics compared to sham. However, 12 Hz and 60 Hz tACS did not yield positive outcomes. Also, Costanzo *et al*. achieved positive outcomes in dyslexics through low frequency rTMS technique (57). In terms of stimulation site, all RCTs targeting the auditory cortex or TPC reported improvements in reading skills in dyslexics after stimulation. However, targeting the prefrontal cortex or SMG had no positive outcomes in the active stimulation groups. Furthermore, all active stimulations concurrently with reading training programs led to improved outcomes in dyslexics. However, the outcomes reported in different studies vary slightly. For instance, Lazzaro *et al*. (26) found that anodal tDCS applied to the TPC did not produce significant group-level results, but it positively influenced participants' behavioral training, suggesting potential modifications in individual responses. While the group didn't show notable improvements, the authors speculated that tDCS might be especially effective for children with severe dyslexia. Their research indicates that NIBS should be combined with behavioral training, as it likely enhances the learning process rather than targeting hypoactivation in specific brain areas.

Discussion

From our findings, we conclude that repeated tDCS sessions, when paired with reading interventions, can effectively enhance reading abilities. Studies indicate that anodal tDCS applied to the left TPC and cathodal tDCS to the right TPC, along with phonology-based reading training, have led to improvements in various reading metrics, including the reading of pseudo-words and low-frequency words. Although these improvements have been primarily noted at the behavioral level, it has been suggested that inhibiting the right TPC while facilitating the left TPC may correct an underlying imbalance thought to contribute to dyslexia. Additionally, neuromodulation of the left auditory cortex using gamma-tACS may enhance auditory processing, particularly for phonemes. The modulatory effects of these techniques can be consistently observed at both behavioral and neurophysiological levels, with tACS resulting in reduced latencies and increased amplitudes in response to auditory stimuli. Generally, examining the results of the NIBS studies reveals a consistent trend, especially among children. Stimulating the left TPC not only enables children and adolescents with dyslexia to read pseudo-words more quickly and accurately but may also enhance their ability to read low-frequency words and texts. Although the neurostimulation primarily influences the decoding process, it seems unlikely to directly affect text reading in teenagers, who tend to rely on sight word recognition despite their reading challenges. In contrast, the findings for dyslexic adults appear to largely align with a neurobiological dual-stream model of reading (58, 59), except that stimulation of the left pSTG results in quicker word recognition and improved accuracy in text reading. However, further investigation is needed to understand how stimulation of these areas impacts network-level plasticity and the activation and deactivation of key reading areas during reading tasks. Importantly, given that only a limited number of studies have explored the ability of NIBS to influence the reading network in individuals with dyslexia, it is important to approach these initial findings with caution.

All tDCS studies included in this review utilized the 10-20 EEG system to determine electrode positioning. In contrast, TMS studies generally employ more precise targeting by using neuronavigation systems to focus on specific brain coordinates (16, 60). While tDCS may lack the precision and specificity of TMS, this aspect could actually be beneficial for therapeutic purposes, as its effects are likely influenced by broader network interactions rather than targeting exact brain regions, which may be unknown. Future research should integrate NIBS with neuroimaging techniques to examine the hypothesized neurophysiological changes brought on by NIBS and to assess whether stimulation modifies functional connectivity among key reading areas. It is important to note that the variability observed across different studies may be partially attributed to differences in stimulation parameters. The ideal intensity for TMS, tDCS, and tACS in researching reading, dyslexia, and other cognitive functions remains uncertain and varies among studies, with tDCS studies typically using intensities between 1 and 1.5 mA. Additionally, the size and arrangement of electrodes can also affect outcomes, while the optimal stimulation frequencies for tACS studies are still not well established. Most cognitive research lacks a consensus on these parameters. Consequently, future investigations into reading and dyslexia should systematically assess the best stimulation settings. For instance, high-definition tDCS has shown promise in improving treatment outcomes for patients with post-stroke aphasia (61, 62), yet no studies have applied high-definition tDCS with dyslexic individuals to date. Such methods may hold significant potential for treating dyslexia.

The effectiveness of NIBS when paired with behavioral interventions, such as reading training, likely indicates changes in synaptic plasticity within the relevant neural network (63, 64). To investigate whether learning outcomes are influenced by modifications in synaptic plasticity, Farahani *et al*. (64) discovered that NIBS primarily modulates existing synaptic plasticity in rat hippocampal slices rather than inducing it from scratch. This implies that integrating NIBS with specific learning tasks may enhance synaptic plasticity in ways directly related to those tasks, creating a "gating effect" on inherent synaptic plasticity. Consequently, NIBS should ideally be used in conjunction with specific training methods for individuals with dyslexia; it may not be effective as a standalone treatment without appropriate behavioral interventions. Additionally, the modulation of inherent synaptic plasticity could account for the frequently observed task-specific effects of NIBS across various types of training or interventions. It is unfortunate that only a small number of the reading intervention studies have examined how stimulation affects brain function. As a result, current research on non-invasive brain stimulation (NIBS) does not provide a solid basis for drawing strong conclusions about the neurophysiological factors underlying the observed behavioral changes. Nonetheless, these behavioral modifications are likely associated with variations in task-related activity in both the targeted and connected brain regions. For instance, nearly all studies conducted by Costanzo *et al*. utilized anodal stimulation over the left TPC/IPL and cathodal stimulation over the corresponding region in the right hemisphere. The authors propose that the behavioral improvements seen in participants may indicate enhanced function in the left TPC alongside a reduction in activity in the right TPC. This interpretation suggests an imbalance in hemispheric contributions to reading, with the right hemisphere playing a more significant role in individuals with dyslexia compared to healthy controls. Thus, it appears that research integrating behavioral training with NIBS could offer initial evidence for the direct modulation of dyslexia-related mechanisms, potentially enhancing new learning and promoting synaptic plasticity through this combined approach.

Future Directions

The presence of several studies with limited sample sizes raises concerns about the generalizability of the findings, potentially restricting their applicability to broader populations. While acknowledging the contribution of these studies, it is important to recognize that small sample sizes can lead to inflated effect sizes and reduced statistical power, ultimately influencing the robustness of the conclusions drawn. To enhance the reliability of future research, it is vital to prioritize larger sample sizes, as this would improve the statistical power and the overall credibility of the results. Moreover, in future research, it is essential for scientists to integrate NIBS protocols with neuroimaging techniques to investigate stimulation-related changes at a broader network level, thereby enhancing our understanding of the neural correlates tied to behavioral changes. Such studies will help clarify how the reading network functions in individuals with reading deficits and how it responds to neurostimulation. Given that NIBS effects can often be less focused than anticipated and that prior research has shown the functional significance of remote effects (e.g., (65)), adopting a network approach will aid in understanding the interactions and functional relevance of various critical regions involved in reading. Additionally, this combined approach can shed light on potential compensatory mechanisms that may emerge in response to disruptive NIBS interventions across the broader network. For instance, earlier studies in the language domain have indicated that inhibiting core language areas with TMS can trigger compensatory upregulation in other left-hemispheric language regions, as well as in corresponding right-hemispheric areas, while also altering task-related connectivity among these (66). Such phenomena are termed compensatory short-term reorganization (67) and could provide insights into the adaptability of the language (or reading) network when faced with challenges from neurostimulation. While current research into NIBS techniques for developmental dyslexia has produced promising short-term results, the lack of long-term follow-up studies significantly limits their clinical applicability. Without understanding the enduring effects of these interventions, it becomes challenging for clinicians to make informed decisions regarding treatment efficacy and sustainability. Addressing this gap is essential to ensure that therapeutic approaches can be confidently recommended for lasting impact on individuals with developmental dyslexia. Finally, the rTMS technique warrants further investigation in dyslexia research because it offers distinct advantages over tDCS and tACS. Its capacity for precise targeting of brain regions and ability to induce long-lasting effects on neural plasticity may enhance reading outcomes, making it a promising avenue for therapeutic intervention in dyslexic individuals.

Limitation

The lack of meta-analysis due to limitations arising from original articles is considered the most important limitation of this study. In addition, the lack of access to all scientific databases to have a very comprehensive search and access to all possible articles is another limitation of this study.

Conclusion

In general, studies utilizing tDCS in conjunction with reading interventions have demonstrated improvements in specific reading subprocesses and skills among both children and adults with dyslexia. Alongside the positive outcomes of tDCS, research employing gamma-tACS at varying frequencies on the left auditory cortex has also achieved short-term modifications in the neurophysiological response to speech and non-speech stimuli. Furthermore, these changes in neurophysiology were correlated with behavioral improvements in various tests measuring auditory temporal processing, a skill that is frequently found to be impaired in many individuals with dyslexia. However, it is necessary to conduct more RCTs that include long-term follow-up assessments to determine the clinical effectiveness of this intervention.

Conflict of Interest

None.

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