Exploring Brain Stimulation Methods to Improve Reading in Children with Dyslexia: A Systematic Review

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ABSTRACT

This systematic review examined 19 studies from 2018 to 2022 that used forms of brain stimulation to activate specific regions within the brain thought to be associated with reading and writing development. All studies were focused on children, aged 7 to 19 (n = 576) with a diagnosis of Dyslexia based on country definitions. All studies looked at first language speakers in Latin based languages. Findings suggest that transcranial direct current stimulation (tDCS) using an anodal electrode in the left temporoparietal region and cathodal electrode in the right temporoparietal region effected change on a neural activity level. Similarly, hemisphere specific stimulation in the form of visual, auditory and the combination of visual and auditory stimulation were applied to create activation in areas known to require greater levels of neurotransmission than is typically found in the brain patterns of children with dyslexia. Forms of rhythmic reading training, action video games, dichotic listening, tachistoscopic visual stimulation, and visual attention focusing training were used as various forms of hemispheric specific stimulation based upon Bakker (2006) Brain Balance Framework. Across all studies, improvements were found including Rapid Automatic Naming (RAN), pseudo-word, low frequency word reading, phonological awareness, reading accuracy and speed to varying degrees. Sample sizes, convenience samples, and research design lead to cautionary optimism of promising results. Forms of non-invasion brain stimulation (NIBS) give researchers great hope for the development of conclusive interventions that will change the neural mapping of children with dyslexia, leading to improved reading fluency and comprehension.

Keywords: *Dyslexia; children; tDCS; NIBS; reading disability; non-invasion brain stimulation; direct current stimulation; hemisphere specific stimulation; education;*

INTRODUCTION

The art of reading and writing is one of the most researched neurobiological processes in modern science (Moats, 2019), due to its clear connection to future wellbeing (Joshi, 2019; Moat, 2019), graduation rates (Joshi, 2019; Lothrop, 2021, Robinson & Thompson, 2019), poverty rates (Leaf, 2020; Lothrop, 2021; Robinson & Thompson, 2019), incarceration rates (Cassidy, 2021; Chow, 2022), and health care costs (Joshi, 2019; Watson, 2019). Literate populations have higher rates of employment and reflect increased country Gross Domestic Product's (GDP) (Rasool et al., 2021; Yun & Yusoff, 2018). many interventions and "learn to read" programs have been developed over the past two decades (Shaywitz & Shaywitz, 2020) because of the importance of literacy.,. Sadly, research has also found that countless students enrolled in reading interventions fail to progress to catch up with their peers in reading, writing, and comprehension (Koen et al., 2018; Turker & Hartwigsen, 2022; Wilcox et al., 2020). Within the last decade, advances and availability of neuroimaging techniques have found distinctions in patterns of neuroactivity between typically developing (TD) readers and struggling readers (Krafnick et al., 2022). As systems of reading interventions do not guarantee advances for all students, researchers have sought to investigate how neuroimaging and brain stimulation can impact future reading and learning skills (Turker & Hartwigsen, 2022). This systematic review looked to explore which processes of brain stimulation coupled with explicit hallmarks of sound reading interventions lead to the greatest positive impact of reading growth.

BACKGROUND

Dyslexia is a profoundly debilitating invisible neurologically based condition that has been shown to affect all facets of modern life. Children diagnosed with dyslexia or Specific Reading Learning Disabilities will have less educational opportunities, struggle more to find employment, and accumulate less wealth than typical developing readers (Joshi, 2019). They will suffer more negative consequences of illnesses and are disproportionately represented in prisons. Current conomic landscape and cultural norms require a level of interpersonal communication and literacy (e.g., social connection through social media) and a rapid acquisition of new skills (i.e., ongoing professional development) (Rasool et al., 2021). Those that do not process these skills, will be left behind. Individuals with dyslexia are shown to have greater difficulty with many of the modules of self-paced learning (Leaf, 2020; Lothrop, 2021). Such limitations are not a result of cognitive ability (many individuals with dyslexia have average and above average levels of intelligence (Chow et al., 2022)). But up until the recent advancements in neuroimaging, and neuroscience in general, we could not fully understand the distinctions in the brains of a typical developing reader and a child diagnosed with dyslexia.

Now, through Functional Magnetic Resonance Imaging (fMRI) scientists have learned that typical developing readers and children diagnosed with Dyslexia have distinctive regions of brain activation when reading (Ramus et al., 2018; Sanfilippo et al., 2020). Functional neuroimaging (fMRI) allows scientists to gather correlational information about brain structures and their function while children are processing language (Turker & Hartwigsen, 2022). Neuroimaging findings have concluded that atypical activation in the left hemisphere of children reflect a profile of reading difficulties found in children diagnosed with dyslexia (Lazzaro et al., 2021b). Combining this revelation is the power to stimulate and supress neural activity in the brain using current technologies. Advances in various types of brain stimulation has prompted researchers to explore reading interventions that combine reading training programs and stimulation to heighten and supress regional brain activity to mirror more typical brain activation patterns.

Sensory Abnormalities Associated with Dyslexia

The importance of fluent literacy during the 21st Century cannot be underestimated. Because of reading's uniquely humanistic quality and its importance to quality of life (Ehmann, Groene, Rieger & Siegel, 2020), it has been a significant research focus for the past 100 years. Developmental Dyslexia is not a new research interest, but with recent advances in neuroimaging, vigour for non-invasive interventions and remediation programs abound. Dyslexia is a condition used to describe the 5 – 15% of individuals that struggle to acquire the skill of reading fluency (Eden & Zeffiro, 1998). With such significant numbers, the discovery of causal and correlational factors will lead to improvements for many children with dyslexia. Competing theories account for dyslexic deficiencies in abnormal processing, magnocellular system, cerebellar or parietal lobe dysfunction or interhemispheric communication that results in low-level sensorimotor inadequacies as compared to control groups (Agnew, 2003).

Over the past 40 years, advances in the mapping of brain activation have led researchers to explore the pathophysiology of dyslexia. Considerations related to abnormal phonological awareness; writing, spelling and motor timing; verbal working memory; and auditory discrimination have all been explored with increasing sophistication (Eden & Zeffiro, 1998). Debate related to the role of visual perception and spatial contrast sensitivity function have been a long-standing controversy within the research field (Franceschini et al., 2022). Concerns of left visual field neglect, related to unstable binocular control is a noted difference between poor readers and fluent readers. Visuo-attentional mechanisms involved in orthographic processing (letter-sound connections) of letter strings and graphemes (written letters) are found to be weaker in 40% of children with reading difficulties (Franceschini et al., 2022). Typical readers have a left-hemisphere preference for neural activation during reading processes. This is not the case for struggling readers. Stein (2001) noted that the temporoparietal language areas on the two sides of the brain are symmetrical without the left-sided higher activation, as found in most neurotypical readers. Researchers have explored various possible pathophysiological links to dyslexia based upon these findings.

A significant debate has persisted around the basis of dyslexia/LD amongst researchers for several decades. Two distinctive camps explain the reading difficulties through specific phonological deficits while others point to sensorimotor dysfunction (Ramus, 2003). Based on a phonological deficit framework, researchers point to the left hemisphere peri-sylvian dysfunction, leading to cognitive impairments with deficient phonological representation and grapheme-phoneme (letter-sound) mapping. Yet others propose deficits in the magnocellular and cerebellar systems resulting in cognitive deficits of the auditory, visual and motor systems; thereby leading to phonological representation and grapheme-phoneme mapping weaknesses (Ramus, 2003). The left hemisphere deficits and impaired efficiency of the interhemispheric transfer of information acts as a posteriori result of the complex involvement of large numbers of neural mechanisms (Rousselle & Wolff, 1991). Agnew (2003) noted that greater task-related neural activation in right posterior putamen and inferior parietal lobule while less than typical activation was found in the left post-central gyrus; indicating parietal lobe dysfunction in children with dyslexia. This literature review includes interventions that address both sensorimotor dysfunctions and phonological training deficits.

Attention has been given to the relationship of the visual motion processing region of the brain and dyslexia. Abnormal visual motion activation and mapping in individuals with Dyslexia have been seen through neuroimaging since the 1990's (Eden et al., 1996). Eden and colleagues (1996, 1998) found that abnormal activation occurred in the V5/MT (part of magnocellular visual subsystem) in all participants with dyslexia. Stein (2001) furthered this research to include the Magnocellular Theory of Dyslexia. His research showed that high frequency and amplitude modulation sensitivity supports stronger phonological skill development, whereas low sensitivity of the Magnocellular pathway impedes phonological skill development. Because the cerebellum, (part of the magnocellular system) applies binocular fixation and speech for sounding out words, a deficit in these areas have led researchers to posit compromised neurological pathways or structures (Stein, 2001). The exploration of increasing event-related potential (ERP) within the phonological linguistic processing within the superior temporal gyrus, Wernicke's area, Broca's area, planum temporale, supramarginal and angular gyri, insula and third inferior frontal convolution are increasingly seeking research interest (Stein, 2001). Further, Stein (2001) cited that poor readers have impaired development of their magnocellular neurones. The structure itself is denser with white matter and therefore leads to delayed and smeared neuronic activation times (Stein, 2001). Such findings add to the interest in neurological structures impacting poor reading acquisition skills.

Another area of interest within pathophysiological differences in the brain include a focus on different eye movement between typically developing and atypically developing readers. Pavlidis (1985) uncovered that the erratic eye movements (EMs) of individuals with dyslexia were not caused by poor reading skills, but that more fundamental structural differences in the brain were in question. Eye movement efficiency typically develops alongside the reading process for most. Over time, eye movement and word tracking become an automated process and therefore more objective to measure. The eye movement records of those with dyslexia are distinctive to simply slow readers and proficient readers. Of particular interest to childhood interventions, Pavlidis (1985) confirmed the inverse relationship between age and duration of fixation, and the number of forward and regressive eye movements. The shorter the fixation period, the faster the information processing. For children with dyslexia, this slowed and erratic eye movement is the focus of some the visual training studies included within this literature review.

Research within the neuropathology for those with dyslexia also considered impaired processing of rapid stimulus sequences. Hari and Renvall (2001) explored the evidence related to "sluggish attentional shifting" (SAS) in individuals with dyslexia. Based upon a attention-related prolongation of word/sound segments, many small deficits were noted. At slower speeds, there is no delays or deficits detected for processing visual information. Hari and Renvall (2001) furthered that a mini-neglect hypothesis (a minor deficit in the right parietal-lobe) could explain the decreased magnocellular input to the dorsal visual stream. This also could reveal the right-hemisphere symptoms associated with left mini-neglect in individuals with dyslexia. Studies included in this literature review explore how the neuroplasticity of the child's brain might alter the very structures through training and neural activation that have been impeding typical reading skill development.

An additional area of brain interest when exploring the pathophysiological aspects of dyslexia include the bimanual coordination. The actions required to read is a complex coordination of several movements simultaneously. The act of reading requires tracking, fast visual scanning of words, holding the text, recognising the print and processing the information, to name a few. Bimanual coordination is required to read. Equally important is a that 40 – 57% of children with dyslexia also have motor impairment affecting coordination, balance and manual dexterity issues (Chaix et al., 2007). Studies showed that metabolic and structural signals in the cerebellar region of dyslexics showed abnormalities (Chaix et al., 2007). Comorbidity rates of developmental coordination disorders were high (55% had dyslexia) (Chaix et al., 2007). Rousselle and Wolff (1991) found that children with dyslexia had bimanual coordination issues as bimanual synchronous and alternating finger tapping tasks increased in speed. Matching rates of tapping to metronome signals with inter-tap rates consistent showed challenging for many children with dyslexia. They concluded that either lateralized left hemisphere deficits in mechanisms of temporal resolution and serial ordering or interhemispheric transfer of information weaknesses accounted for many of the coordination deficits found in children with dyslexia (Agnew, 2003; Rousselle & Wolff, 1991). It remains unclear if this is part of a subtype of dyslexia or a coincidental finding.

This literature review explores various brain stimulation techniques focused on the unique characteristics of a children with dyslexia. The areas of stimulation and remediation focused on the above-described regions of the brain that activate differently than those individuals in control groups. Although many types of brain stimulation studies are available, the focus of this literature review is limited to Transcranial Direct Stimulation and Non-Invasive Brain Stimulation. Transcranial Magnetic Brain Stimulation is not included in this review and is a related modality worthy of further exploration.

TYPES OF BRAIN STIMULATION

There are two general classifications of brain stimulation under review in this paper: Transcranial Direct Current Stimulation (tDCS) and Non-Invasive Brain Stimulation (NIBS). Within the limitations of this systematic review, both are forthwith annotated by their shortforms. Although deep current stimulation can be invasive, the forms of tDCS included in this review are superficial to the skull and therefore are well tolerated by child participants within these studies.

Transcranial Direct Current Stimulation (tDCS) is a tool that permits the researcher to manipulate (stimulate/excite or inhibit/supress) neural activity within proximity to the electrode placement on the skull (Lazzaro et al., 2021a). Anodal placement acts to stimulate the area whereas cathodal inhibits or restricts activation of the neural pathways. In the studies reviewed, the left temporo-occipital and left temporo-parietal regions received anodal montage with some cathodal placements in the right parieto-temporal regions (Rahimi et al., 2019). As it is known that children with dyslexia (and adults) have a hypoactivation in the language process regions found in the left temporo-parietal regions (Lazzaro et al., 2021b), and over activation in the right hemisphere, tDCS acts to balance the neuroactivity in the brains of people with dyslexia (Bergemann et al., 2020). The left temporo-occipital regions are essential for automatic visual processing of print and the left temporo-parietal regions are important for grapheme-to-phoneme mapping. An activated left temporo-parietal region allows the visual representation of graphemes (letters) to their phonemes (sounds) allows readers to fluidly interpret text and sound interchangeably. By increasing neural excitability of the left temporo-parietal areas while reducing the neural excitability of the right temporo-parietal areas in children and adolescents with dyslexia repeatedly, pathways and neural activation patterns can be sustained over time. Any dysfunction of the visual selective attention, rapid auditory sensory processing, auditory selective attention systems or the magnocellular-dorsal (MD) stream led to difficulties in reading for children with dyslexia. The tDCS, therefore, applies a targeted weak current (following various protocols of variable, repetitive or oscillatory pulses), in order to modify plasticity of the area. Although the direction of the polarization is dependent on the orientation of the axons and dendrites, generally, anodal increases excitability in hypo-activated regions and cathodal reduces excitability. When additional electrical current is applied to hypoactive regions, greater neurotransmissions can occur. Due to the greater neuroplasticity in children and adolescent brains, as compared to mature brains, the effect of these interventions holds great promise for possible re-organization of dysfunctional neural networks. This review will only cover transcranial electrical stimulation (tES), transcranial alternating stimulation (tACS) and transcranial random noise stimulation (tRNS). Although transcranial magnetic stimulation (TMS) does also hold some interesting findings, these studies were excluded from this literature review. This is not to suggest any generalized findings in particular, but to acknowledge that other exclusion criteria led to less studies that matched the parameters sought.

Similarly, NIBS has shown pro-cognitive effects amongst children and adolescents diagnosed with dyslexia. The high tolerability, without known risks for harm, of this form of intervention, makes it increasingly popular amongst researchers, medical practitioners, parents and educators alike. Due to the little effort required by the participants, this is an ideal form of intervention for children that have experienced great fatigue and apathy when trying to improve their functional literacy. Despite NIBS documented positive outcomes, this form of intervention is still considered an alternative intervention. Researchers still do not understand the working mechanism that result in these changes of the brain function albeit neuroimaging confirm the findings (Bergemann et al., 2020).

Hemisphere specific stimulation (HSS) is taking advantage of the contralateral relationship between body and the brain. By using one side of the body, one can send messaging through the central nervous system and thereby stimulate the opposite side of the brain. Hemisphere-specific stimulation through lateral visual fields (HSSvis or vHSS) is done by flashing words on the opposite side of the brain that requires further stimulation. Importantly, between flashes of the word, the child must re-orientate their gaze to the centre of their visual field. Bakker (2006) defined L-type dyslexic children benefit from the word appearing on the left side of their visual field and P-type children with dyslexia benefit from the stimulation of the visual field on the right side of their visual fields. Bakker's (2006) Balance Model and findings have been replicated in several studies included in this review. As part of this literature review, Lorusso et al. (2021a) and Koen et al. (2018) have enveloped the understanding of these neurological sub-type distinctions in individuals with dyslexia into their research design.

In principle, transiently modified neural activity change functional neural network interactions, changing through plasticity and altering behaviours to improve cognitive function. Transcranial magnetic stimulation (TMS), hemispheric-specific stimulation (HSS) through auditory pathways (aHSS), visual pathways (visHSS) and tactile pathways (tacHSS) and attentional selective pathways through the use of Action Video Games (AVG) have all shown non-invasive means to change cognitive functionality.

NEUROBIOLOGY OF DYSLEXIA

The neurobiology of dyslexia is still evolving. Reading is one of most complex processes for humans to learn. This is because it involves several regions of the brain and these regions change in their roles and dominance during the maturation of the brain. Reading is a relatively recent evolutionary function. It relies on establishing a visual interface with oral language and then processing that spoken word into phonological areas of the brain with graphical representations. This neural process is no small accomplishment. The reading network involves three key circuits: left dorsal temporo-parietal, left inferior frontal and left ventral occipito-temporal circuit. Kearns et al. (2019) describe a neurobiological dual-stream model of reading. The posterior inferior frontal gyrus (pIFG) stores sound information in sequence of occurrence. The temporo-parietal cortex (TPC) then utilizes substructures (posterior superior temporal gyrus (pSTG), supramarginal gyrus (SMG) and angular gyrus (AG) to convert these sounds into graphene associations. Each of these processes are highly intertwined therefore weakness or dysfunction of any of these components lead to reading challenges. Finally, the occipito-temporal cortex (OTC) has a debated role including orthographic coding, multimodal neuronal encoding or written language encoding (Kearns et al., 2019; Turker & Hartwigsen, 2022).

Coltheart (2006) first coined the duals route cascaded model (DRC) to explain the dual routes that word recognition graphene-to-phoneme conversion occurs. For high frequency, sight words, the lexical pathways are processed through the ventral pathway. This pathway includes middle temporal gyrus (MTG), the occipito-temporal cortex (OTC) and the IFG. Whereas the dorsal pathway includes the left OTC, STG, SMG, AG, and precentral gyrus through the motor cortex to the left posterior inferior frontal gyrus (IFG) (Kearns et al., 2019). As children with dyslexia have less sight words and that it is more challenging to transition previously seen words into automatic sight words, the process of reading is slowed, travelling through the more complex dorsal pathway. Van der Lubbe et al. (2019) found that the left lateral geniculate thalamic nucleus was smaller in individuals with dyslexia. This further reduces the processing capacity of the indirect magnocellular pathway.

The magnocellular-dorsal (M-D) pathway is a critical processing stream necessary for reading. The M-D pathway travels through the retina to the M layers of lateral geniculate nucleus and then through the primary visual cortex. While reading, a person quickly must scan the letters of the page, recognize them as a word, then move to the next word almost instantaneously. The M-D pathway, in particular, prefers these fast movements or blurred visual contours. It is closely associated with reading processes. This more circuitous processing route, could also explain slowed reading fluency. Whether this biological disadvantage explains part of the difficulty to automate reading is still unclear.

Purpose of Systematic Review

The aim of this systematic review was to examine the most recent (2018 to 2022) tDCS and NIBS studies involving children and adolescents with dyslexia. These studies continue to add to the collective knowledge supporting our neurobiological understandings of neuroanatomical and neurofunctioning of young individuals with a diagnosis of dyslexia. Furthermore, the review aimed to extend confirmatory acknowledgement of the promise of these types of interventions to supplement research-based reading intervention programs. Combining brain stimulation and sound reading training interventions at a young age holds the promise of changing the opportunity trajectory of individuals with dyslexia. Finally, applicability, generalization of practices and limitations of current research were noted to support future scholarly research.

PURPOSE OF SYSTEMATIC REVIEW

Search Strategy

The search methods for the present review followed the Preferred Reporting Items for Systematic Reviews and Meta Analysis (PRISMA) guidelines (Moher et al., 2009; see Figure 1). Eligibility criteria included:

1. The study applied NIBS or tDCS protocols (either single session or multiple sessions) with either between or within-subject design or blind design and that a cortical brain region targeted by its design involved in reading.

2. That the study involved children or adolescents with a diagnosis of dyslexia based on country definitions and stipulations.

3. The study applied a reading measure or reading-related task with a primary aim to use brain stimulation protocols to induce changes in reading function.

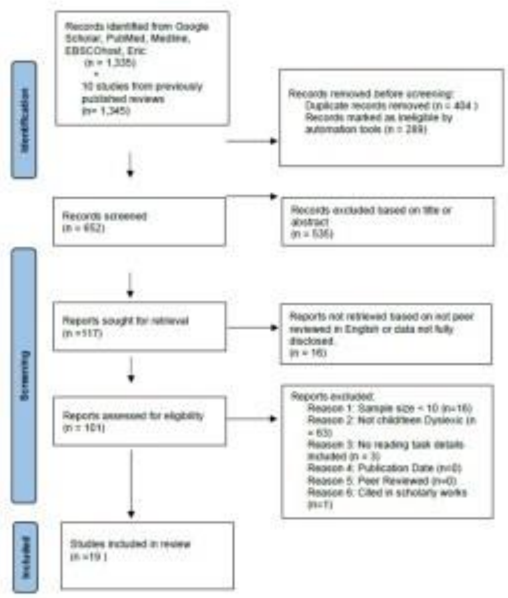
4. That research was published after 2017.

5. That all research was peer reviewed and found in scholarly journals or publications.

6. All works were cited in other scholarly papers.

Identification of Studies via Databases and Reviews

Figure1. *PRISMA flowchart displaying the process of literature search and screening (see Moher et al., 2009). Cut-off date for publication of studies was August 2022.*



First, general studies matching the criteria were reviewed using the words “Dyslexia” and “NIBS” and “reading intervention”. A second search included the search parameters of “Dyslexia” and “Hemisphere-Specific Stimulation” and “reading intervention”. A third search was made for “Dyslexia” and “action video game” and “reading intervention”. These search parameters were used through PubMedMedline, Eric Ebscohost and, Google Scholar databases. Initially 1,345 records resulted. Google Scholar produced the most studies, but after 400, the search relevance declined and were excluded. After a preliminary sorting of sources, systematic reviews were scanned for additional studies that could be added. Utilizing a snowball or network effect, additional 10 studies were added for initial review. Additionally, 534 primary reviews excluded studies based upon titles or abstracts. The remaining 117 titles were further reduced by eliminating those without peer reviews in English (n=2) and those that all data was not included in the publication (n=14). This left 101 studies to scrutinize. Of those remaining, 16 were removed for small sample size (n < 10). Sixty-three studies were eliminated for adult populations as their focus. Three additional studies were excluded due to reading task details not included in the publication. Finally, one publication was not cited by another scholarly writer. Overall, 18 experimental studies met the eligibility criteria and included in this systematic review.

Participants/Subjects

All studies included followed ethical practices where parents/guardians gave consent for their children to participate. Studies typically had an age range of 8 – 14 years old, with one study including 7-year-olds, another included ages up to 16, with another study (focused on adolescent participants had an age range of 16-24 years old). Finally, one study included children 9 years up to the age of 18. One-hundred-and-fifty-one participants were in the reviewed tDCS studies. An additional 448 child and youth subjects were included in the NIBS studies (aHSS, vHSS, AVG, RRT). Of the NIBS studies for children, the median age was 9.01 years old. The median age in the tDCS studies was slightly older at 14.57 years. As these studies required slightly more invasive methodologies (electrode montage and applied current to the head), older children may have been more receptive to the process than younger children.

RESULTS

NIBS and tDSC Studies Reviewed

Not accepting that many current stand-alone reading interventions have not resulted in literacy fluency necessary to meet employment and wellbeing aspirations, the importance of exploring a dual path of intervention for those with reading disabilities or dyslexia in the studies analysed as part of this literature review, most common NIBS and reading interventions, were explored. Several studies indicate the promise of combined interventions using NIBS as one of the components for reading improvement. Turker and Hartwigsen (2022) contended that non-invasive brain stimulation (NIBS) not only modulates brain function but can enhance cognitive functions. Their research suggests that the utilization of such protocols have profound implications for how learning disabilities such as dyslexia improve learning outcomes. Turker and Hartwigsen (2022) also emphasized modulate auditory cortex function as a preintervention and intervention approach for affected children. Although the majority of the studies explored here followed the path of excitation of left TPC (including the posterior meddle and superior temporal gyri), others approached it differently.

Seven studies applied transcranial electrical stimulation in the forms of tDCS or tACS. Notably, some studies explored the auditory and visual attention used NIBS techniques involving both the auditory and visual processing cortices. While it is too early to attach causal outcomes to these various combined interventions, there is much promise in the amassing results, with clear areas of brain stimulation for concerted future research. More significant and longer lasting results were seen in studies that involved repeated or multiple NIBS sessions as compared to single session formats. This is a logical outcome of human learning and neurobiology. Repeated actions strengthen neuro-connections. And although it is beyond the scope of this research, it should be noted that the maturity of the brain effected the areas of the brain that resulted in most growth.

tDCS Results

Constanzo et al.'s (2019) work showed a significant improvement in text reading accuracy, low frequency word and non-word reading for a bilateral stimulation with left anodal/right cathodal tDCS (i.e., acting to excite left TPC while inhibiting the right TPC). Additionally, Lazzaro et al. (2021a) furthered Constanzo et al.'s (2019) research by adding attentional focusing while providing both stimulation and reading training. In Constanzo et al.'s study, researchers applied tDCS left anodal and right cathodal of the left TPC. The conclusions of this study shared previous results of word and pseudoword reading but not as significantly. What did result was improvements in text reading fluency, due most likely to the visual attention focusing and working memory training. Those with the greatest gains in visuo-spatial training also showed the greatest overall improvement in word, pseudoword, and text reading.

(See **Table1.**)

Rahimi et al. (2019a) used a semi-experimental method with a control group. There were 15 children in three groups: a) control group, b) tDSC group and c) tDSC group that also received cognitive training. The Visual Attention tasks (CogLab software) subtests, The Simon Effect and the Discovery of Change, were utilized to explore congruent and incongruent response indicators, as well as the rate of correct responses. The tDCS electrode placement was 5cm by 5 cm area on the dorsolateral prefrontal lobe of the left hemisphere with a 1.5 milliamper for 20 minutes. The cognitive training was a series of 11 games that supported attention skills, alphabeticity, phonic, phonological awareness, spelling, pronunciation, and mathematical skills. Using a Multivariate Analysis of Covariance (MANOVA) method, the researchers found linear relationship between dependent variables. Cognitive training with tDSC resulted in positive effects for visual attention processing. These results aligned with others in this literature review (Rios et al., 2018, Rahimi et al., 2019a). Similar to Lazzaro et al., (2021a, 2021b), Rahimi (2019b) also noted reading speed increases. Training for visual attention, through training and stimulation results, were also echoed in NIBS studies of Cancer et al. (2020) and Franceschini and Bertoni (2019). Rahimi et al. (2019a) posited that the tDSC stimulation change neural sensitivity allowing them to depolarize or hyperpolarize brain cells in the regions responsible for visual attention and executive functioning.

Rios et al. (2018) used a single session format, stimulating the pMTG of dyslexic children. In this study, confirmation was sought that the L pMTG region was key in sound-symbol associations for developing brains. Rios et al. (2018) found that the task of reading pseudowords after tDSC of the L pMTG led to improvements, whereas the syllable, letter and single word reading skills was unchanged. The researchers' next steps were to arrange articipants into subgroups by age to see if more detailed patterns arise.

Rufener et al. (2019) focused their research on tRNS of the left auditory cortex intending to effect phoneme categorization in adolescents (and adults, not included in this review). Three stimulation sessions of the left auditory cortex were administered, while the participant completed a phoneme-categorization task. Participants were able to more accurately perceive the time between air release and vocal cord vibration compared to the sham controls. Thereby, authors concluded that auditory perception was enhanced. This was confirmed through EEG recording and increase of amplitude of the auditory response (P50-N1) when compared to the sham control group. Before the brain is fully mature, it can be beneficially changed at the neurophysiological level (results were reverse in adult participants).

Rahimi et al. (2019a) used tDCS on the left STG in children and adolescent participants. Twenty minutes of bilateral stimulation of the STG (anodal on left STG and cathodal on right STG) while participants indicated time differences between white noise and long-latency auditory-evoked response to speech. Modulated amplitudes of P1 & 2 and N1 were active by speech. As amplitude was increased, latencies of responses were reduced as compared to baseline and sham control. This study showed that threshold values decreased for activation and that improvements were found in accuracy. Implications to improved central auditory processing could indicate a remodelling of the deficit auditory and temporal information processing as profiled in children with dyslexia. Combining this with reading intervention training led to higher accuracy in noise gap tests, and statistically significant improvements in auditory discrimination tasks (when Left AC stimulated).

Lazzaro et al. (2021a, 2021b) contributed two studies of particular interest in this systematic review. Both followed similar experimental designs using a RCT blind construct, one including a double blind and the other a single blind. The double-blind experiment also contained a sham control, making it potentially less biased than the other. In both experiments the location of the electrodes were identical (Left Temporoparietal Junction), which is very important for visual, auditory, and somatosensory systems. Both sets of participants received 1 mA of current (slightly less than Rahimi's design), and yet this too resulted in increased neural sensitivity of the TPJ. The difference in the design was the number of sessions the participants received. As one would expect, when the tDCS was continued over 6 weeks, the effects were longer lasting and slightly more pronounced than the initial experiment, with a single brain stimulation. Finding the optimal protocol of amplitude, duration, and tDCS rehearsal is an ongoing search amongst researchers.

Consistently, across the studies included within this review, tDSC showed positive effects on areas of the increased activation and inhibited activation within the brain. The use of anodal (left hemisphere) and cathodal electrodes (right hemisphere) positioned in specific regions led to observable improvement in reading or components of reading in children diagnosed with dyslexia and those with reading disabilities in general. Although not in the scope of this review, it should be noted that Cancer & Antonietti's (2018) work showed a distinction depending on the age of the participant. If the tDSC was applied to adults, improvement was seen in the area of decoding, whereas children (included in this review) saw greater improvements and in different areas (non-word and low-frequency words) which act for building blocks of more complex, and unfamiliar words (Cancer & Antonietti, 2018). Throughout all of these studies, the importance of visual attention was explored with some notable finding. These was a great deal of replication in the studies with similar findings across the set.

NIBS Studies Results

Within the parameters of this systematic review, ten studies met the inclusion criterion for review. A combination between visual attention, auditory and mixed sensory attention made up the included experiments. Five studies explored visual attention training as the key to reading improvement. One study explored auditory training and the remaining four studies looked at the shared importance of both visual and auditory training together as a means towards improvement. In all the studies reviewed, there was noted improvement and change compared to control groups and pre and post-tests. Similar to tDSC studies, there was variation between the duration of the training and the time span between multiple sessions. Research has yet to come to a consensus on the most effective hemispheric specific stimulation or visual and auditory stimulation that result in the most profound improvements.

There are three NIBS subspecialities that account for the majority of hemispheric specific stimulation. These include auditory, visual, and tactile stimulations. Based on the work of Bakker's (2006) Balance Model, and building on the theories of learning for multiple intelligences (Shearer, 2018), researchers contend that using other modalities of learning can complement primary learning pathways. As the process of reading involves visual and auditory sensory and processing systems, these two types of NIBS stimulation were found more frequently in the research.

Auditory Stimulation

Five studies used auditory stimulation either primarily or secondarily to enhance neural activity in the NIBS section of the research. In these studies, the Rhythmic Reading Training (RRT) created phrasing that the brain used to pace the processing of the words broken down into sub-sections. This timed tapping of a metronome type stimulus aided the children in taking the right amount of time to capture the phonetic sound in order to decode. And although the specific studies will be discussed in this section, it should also be noted that Rufener et al. (2019) used Transcranial electrical stimulation (tES) to explore the auditory processing implications on phoneme processing. Rufener et al. (2019) alternated current stimulation and transcranial random noise stimulation (tRNS) over the entire auditory cortex. This evoked brain response patterns representing low-level sensory processing. This practice created increased phoneme-categorization acuity.

According to Rufener et al.'s results between no stimulation, tACS, and tRNS, the tACS methodology showed the importance of the auditory system for improved reading. Analysis methods of t-test indicated that tACS-related participants showed significantly different outcomes from zero (T (15) = 2. 385, p=. 032) for children.

Interestingly, adults had greater improvement using this method, suggesting that the reading process changes over the lifespan of the individual. In short, auditory stimulation acts to incite pre-attentive processing centres, readying the temporal lobe for reading comprehension. This pre-attention is thought to be an important process for those with specific reading learning disabilities including dyslexia (Rufener et al., 2019). Pre-attentive auditory processing appears to increase accuracy in phonological-based training (Brazen et al., 2020). Rufener et al.'s (2019) research, although interesting and compelling, only had 30 participants (15 children, 15 adults). This is a limitation of this research. Similarly, Cancer et al. (2020, 2021, 2022) found that by cueing the brain through auditory processing (older brain system), that it alerted systems to activate.

Visual Stimulation

Bundesen and Giaschi (1990) consolidated the understandings and importance of visual recognition and attentional selection when computing the single-stimulus recognition necessary in reading. The visual attention span (VAS) is required for the brain to process and interpret print material. Typically, VAS is shorter in individuals with dyslexia compounded by the slower MD processing route (Badcock et al., 2011; Brazen et al., 2020). This means that a targeted visual stimulation protocol could act to enhance (through speed and memory spans), as well as allow neurodivergent individuals the time to process the information with greater accuracy (Brazen et al., 2020).

(See **Table2.**)

Visual stimulation can be done in a variety of ways, but generally involves computer-based learning equipment in research (this controls for variability factors, and therefore results are more replicable). Some studies tested Action Video Games (AVG) to increase attention to visual stimulus. These programs (e.g., Fruit Ninja®, Plants vs. Zombies: Garden Warfare®, Nanostray 2®), specifically work with children's attention and focus. Programs such as Tachidino® learned where the child's reading errors were and focused attention on those areas. Computer-guided learning shows promise for personalized training for children with dyslexia.

Other studies that combined auditory cueing and visual stimulation (Cancer et al., 2020, 2021, 2022; Franceschini and Bertoni, 2019; Lorusso et al., 2022) were attempting to combine the strengths of two systems to increase learning. The general findings of the studies included, showed both short-term and longer-term verbal memory deficits in children with dyslexia. Therefore, the focus of these studies was to enhance the neural activity in both the auditory cueing and visual stimulation brain regions. Repeatedly, studies have noted that dysfunction in the Magnocellular-based visual-motor intervention (MD) stream are found in children with dyslexia (Boden & Giaschi, 2007; Stein & Walsh, 1997; Vidyasagar, 2019; Werth, 2021). Sluggish dorsally-driven inhibition of return can impede orthographic processing in individuals with dyslexia (Franceschini et al., 2018).

In Computer-Guided Reading Strategies, Werth (2021) studied how extended affixation on word segments could increase word reading accuracy. After completing a diagnostic on a computer to determine the instructional range for the child, the computer altered the length of time that participants saw comfortable length word segments. By slowing down the rate of reading, accuracy improved significantly. The chunking of the word segments also allowed dyslexic readers to recognize the sound before moving to the next chunk. Having a centred visual point before seeing the word segment also engaged the brain bilaterally. This bilateral stimulation would also assist in the integrated activation of the brain. As the visual field of attention narrowed, the participant more closely saw the letters and was not distracted by other information. As these words were pseudowords, the participants would not have an advantage over other readers. There were two controls – one with typical readers using the computer aided pacing and one without any computer interface. It was found that typical readers had higher accuracy when they could see the entire word, whereas children with dyslexia had a 69. 97% improvement in their pseudoword reading accuracy (Werth, 2021). Werth (2021) also disproved that visual crowding did not impact dyslexic readers. If it had been, then the middle syllable or word segment would have more errors and it did not. More frequent errors increased at the end of the words. Longer fixation time did allow participants to process correctly larger word segments, suggesting it is visual attention span or the verbal short-term memory that is creating difficulties compared to typically developing children.

Caldini et al. (2020) used visual attentional training to improve reading amongst 25 children with dyslexia. Their study included a 25 matched typically developing readers as a control. Caldini et al. (2020) used two training tasks of oculomotor (saccades and pursuit movements) and three visual searching tasks. The children did the training two times for 10 minutes each with a rest in between. During these tasks, the eye movement was tracked using Eye Brain T2®. Saccades, prosaccades, fixations, and regressions were tracked. A univariate one-way ANOVA was performed showing that there was a significant training effect for total reading time $p < 0.03$ and that only the group with training increased their speed between trial 1 and 2 ($p < 0.0001$). With a very strong β result of $\beta = 0.45$, the significant interaction of training with the results can be strongly associated. No changes in saccade or prosaccades were noted, suggesting that duration of the affixation translated into comprehension. Caldini et al. (2020) furthered that those dyslexic children participating in the study became more efficient in extrapolating phonological meaning correctly. This suggested that visual attentional training could act on the neural processing network, rather than the motor network. They also noted that more inattention aligned with reduced activity in the left intraparietal sulcus and left middle frontal gyrus (Caldini et al., 2020).

Koen et al. (2018) looked at hemisphere-specific stimulation on reading fluency in children with dyslexia. The age range of participants considered children ranged between 8 and 19, which was older than all but 2 studies included in the review. Their areas of focus were the left superior temporal gyrus, the left inferior frontal gurus, and the left inferior occipito-temporal/ fusiform area (visual-word form area). The small study involved 15 participants that underwent fMRI imaging during program training periods and postintervention activity mapping. Participants were determined as L-

Type, P-Type, or M-Type children with dyslexia, according to Bakker (2006) Balanced Model protocol.

Bakker's (2006) research suggests that brain activation levels in specific regions highlight the stage and deficit of reading consolidation. For L-Type Dyslexics, Bakker utilized fMRIs to show lower-than-optimal neural activation in the right hemisphere of the brain, as compared to neurotypical fluid readers. Right hemispheric stimulation would increase neural activity in the brain to increase event-related potentials (ERP). With enhanced stimulation of the visual-perceptual regions of the brain, Bakker (2006) suggested that reader's proficiency could be improved. It is important that this stimulation matches the neural activity deficit mapping of the individual. P-Type participants, required phonetic stimulation and therefore required right visual field stimulation or left hemispheric stimulation. M-Type participants, showed unusual event-related potentials (ERP) in both brain hemispheres control. In this type of Dyslexic learner, periods of concentrated stimulation would begin in the right visual field, and then move to the left visual field.

Using FlashWord® vHSS program, researchers were able to modify the programming to reflect the dyslexic subtype. Results showed a reduction in activation in over-excited areas, creating a more typical neural mapping of activation for readers. Twelve participants saw increases in words per minute reading rates. Additionally, 12 of the 15 participants improved the grade level that they were reading at. Of the three participants that did not improve their rate of reading, they did improve their reading level of the initial group. Similarly, those that slowed in their reading, showed an increase in the grade level that they were reading at including the second groups results, there was a total of 2 participants that showed slower postintervention scores in both areas. These outliers, due to the small sample size, changed the effect size for all involved. No patterns of L-Type, P-Type, and M-Type were detected to explain these differences. There was measured evidence to show neural processing differences after the intervention. Consistently, the neuroimaging showed higher amplitudes of activations in the regions of interest. This includes the sound/symbol associations of the STG, the encoding phonological features of the IFG, and the automatic word retrieval in VWFA. It is thought that higher STG activation could indicate that IFG is supported in the primary and auditory association cortex.

Peters et al. (2021) utilized vHSS training through an Action Video Game (AVG), Fruit Ninja® with children between the ages of 8 and 13. Different from most recent studies, the researchers limited the training time to five hours (down from the 12 hours of the other similar studies). This study had three groupings: a) AVG plus group training, b) AVG training plus individual program reading training and c) control group. Their findings support a significant interaction between time spent and intervention for reading accuracy with Group 1 increasing by an equivalent of 6.31 months and 8.55 months equivalent for Group 2. Group 3 did also show small gains of 1.26 months by the time of the post test. Reading rates also showed strong gains for the AVG groups. The AVG plus training saw a 17. 82 months gain, whereas the AVG training with individual training resulted in a 19.9 months equivalent gain. The control group declined by -1.48 months. Rapid automatic naming saw an increase of 10. 82 months for Group 1, 17.28 months for Group 2, and 1. 1 month's equivalent of advancement for Group 3. The Group 3's growth represents the natural growth in reading between pre and post testing. No conclusive results were found with the magnocellular temporal processing.

Lorusso et al., (2022) used a combination of AVG and tachistoscopically presented words and auditory reading to improve peripheral processing and global perception that was spatially temporally unpredictable. In this study, 91 participants used a program called Tachidino®. Unlike many studies, participants were able to other LDs and/or ADHD. The participants were put into 3 age groupings (< 9 years old; 9-10 years old; and over 11 years old). This study further identified the participants in classifications of severely impaired children with dyslexia and moderately impaired children with dyslexia. The trial groups were further divided based upon initial reading speed, reading accuracy and writing accuracy. The average time spent on the training was 14 hours with a range of between 12 and 18 hours in 20-to-30-minute blocks. Initially, children used the attention training component of Tachidino®, then this was followed by the decode/ encode part of the program. Word and letter placement aligned with protocols of Bakker's Balance Model of L-Type, P-Type, and M-Type forms of dyslexia. After four weeks of training, or a control, the groups were tested, and then six months later. Promising results showed that the more severely impaired children had the greatest gains and rapid, central (rather than lateralized) stimulation provided the most effective writing stimulus. The researchers concluded that writing (different than reading) benefits the most from bilateral stimulation due to its inter-hemispheric integration (Lorusso et al., 2022). Significant treatment x age effects resulted with the youngest group showing the most lasting effects and syllables/second. Speed and accuracy rates were not affected by age. At the six-month follow-up, Lorusso et al., (2022), concluded that these advances were maintained through behavioural and ERP measures taken. Overall, the more time spent using the program showed greater improvement with a moderate effect size. Reading speed, accuracy and writing accuracy improvement all resulted from this intervention.

The three studies formulated by Cancer et al. (2020, 2021, 2022) all looked at a combination of auditory and visual stimulation as a means of improving reading in children with dyslexia. Each study had a control group and then a group of children in the intervention. The children ranged in age from 8 – 14 years old and the experimental group completed Rhythmic Reading Training (RRT) and visual stimulation. Each study had multiple sessions of training (7.5 hours, 13.5 hours and 7.5 hours respectively) (Cancer et al., 2020, 2021, 2022). Consistent results were found in all three groups. The 2021 study looked at if a remote delivery model changed the results and they did not ($\eta^2 = 0.02$). With replication, the studies showed that vHSS through AVG combined with RRT and RRT alone improved pseudoword reading, speed, accuracy, and phonological awareness. RRT was attributed to improved RAN and attentional abilities across the studies. RRT did not reach statistical significance for perception/reproduction. A negative correlation was found between Rhythm Reproduction (Stambak test) and improvement in RAN speed. A similar negative correlation was also found between sound length discrimination and reading accuracy and RAN accuracy. It was also found that AVG without complementary literacy training improved reading scores amongst Italian children with dyslexia (Cancer et al., 2022). This finding is consistent with improved visuospatial attention capabilities.

Helland et al. (2018) explored the use of auditive training through a dichotic listening app. Building on the knowledge that laterality, processing, and attention are different amongst children with dyslexia and those that are neurotypical, Helland et al. (2018) devised a three-group research design; group a) control training; group b) dyslexia training and group c) no training. Using dichotic listening taps, the researchers found that RAN and DS scores correlated significantly with dichotic listening measures. This would suggest that typically developing and children with dyslexia have similar lateralization, but that weaker modulation of attention explains the distinctions in reading development. Dichotic listening requires a person to identify a sound in one ear while simultaneously ignoring the sound in the opposite ear. The participant may be asked to report on the more easily identifiable sound in either ear or a sound in a particular ear. When there is a right ear advantage (because the typical language processing pathway is contralaterally on the left hemisphere), the participants show superior processing capacity (Helland et al., 2018). When there is a left ear advantage, as is for many dyslexic children, the neural pathway to reach processing in the left hemisphere is more circuitous. Researchers had hoped to find statistically significant changes in the attention shift index (ASI), but did not. Moderate to strong correlations were found between RAN, DS, and dichotic listening training. It was also found that the faster the participant's RAN task scores, the higher their ability to suppress left ear listening. Helland et al. (2018) confirmed that good language processing and verbal working memory skills rely on the ability to shift attention as a cognitive underpinning. Increasing attention focus and shifting are necessary for improvement within reading attainment.

Discussion

There is consistency and promise in the field of non-invasive brain stimulation for children with dyslexia. Across the reviewed 19 studies involving both tDSC and forms of hemisphere-specific stimulation, all studies showed some improvements to measures of reading components. Auditory and visual-spatial attention have been found to support reading development in children with dyslexia. Consistently, the most gains were sensed with younger children that received more sessions of brain stimulation, while also receiving reading intervention training. There was also increased significance when the form of intervention mapped directly to the subtype of dyslexia (P, L or M) and using multiple modalities.

The tDSC forms of exciting and supressing brain regions of interest showed consistent trends of allowing more typical reading responses. Although the protocols for amplitude, and session frequency/duration varied between studies, all included studies showed that neural networks responded to the stimulation protocols. Studies involving fMRI were able to capture the changes in neural activity patterns through pre and post intervention sampling.

Across the reviewed research some consistency of stimulation protocols was arising, but not absolute. Due to the nature of the brain, finding the optimal protocols will be difficult. Studies included a range of stimulation thresholds for direction stimulations (between 1-2 mA for tDCS), stimulation locations and a range of EEG systems and guides for electrode placement. Without such protocols, larger scale studies with generalizability will continue to elude researchers.

Studies indicate that NIBS and tDCS protocols that involved multiple sessions over time, coupled with reading intervention programs showed the greatest gains and sustainability over time. Duration and repetition act as the amplification of modulation both behaviourally and neurophysiologically. Initially studies have shown either improvements behaviourally or neurophysiologically, but further research to combine these aspects will help move our understanding of sustainable beneficial interventions more clearly. We speculate that anodal tDSC over the left TPC and cathodal tDCS over the right TPC acts as means to modulate the atypical brain activations found in children with dyslexia to more neurotypical patterns. Studies consistently noted that when combined with reading intervention programs/training, children improve along several reading skills, including pseudoword or low frequency word reading. Next steps would include the examination of neuroimaging techniques to compare neurophysiological baselines in participants prior, during, after and time-delayed neurological brain mapping. Complicating this exploration is the uniqueness of individual brains and functioning. Discovering the precise setting and location of stimulation for individual success is still outside of current research capacities.

Through neuroimaging, it has been established that the neurological activations in a typical reader's brain and that of a child with dyslexia are different. It is thought that the imbalance of hemispheric activation for children with dyslexia require stimulation and inhabitation of the brain to modulate a more typical brain activation (Turker & Hartwigsen, 2022). By exciting the left hemisphere while inhibiting the over active right hemisphere, studies indicate that temporary and immediate behavioural progress can be observed. It is also thought that activation pattern resembling more closely typical child readers may strengthen synaptic plasticity and reduce the signature aberrant brain activation patterns found in children with dyslexia.

Limitations of Current Research

All results must be taken with optimistic caution. The research design in most of the studies was weaker than desired. The most significant limitation of these studies is their relative effect size. Such small sample sizes without double blind or sham controls may have resulted in researcher bias. As in a few studies, outliers impacted findings and were noted as an explanation of why results were not as significant, so too must it be acknowledged that skewed results can occur with small samples.

The studies included in this literature review fit into other studies that examine adult populations with dyslexia. The most intriguing part of these childhood studies is the potential to follow the participants into adulthood. With research suggesting that the adult brain with dyslexia is different than the child's brain with patterns of dyslexia, this aging of participants could lead to some very interesting outcomes.

This systematic review found limitations in the 19 studies. They indicate a need for larger studies, and perhaps earlier studies with children under the age of 7. The other skewing of this data could be related to the parents that decided to allow their children to be involved in these types of studies. A protective factor for any child is an engaged parent. To assist with the transport to appointment and the completion of the trials indicates a level of parental capacity that may have excluded some marginalized children. Those without medical care and diagnosis would mean that many children were not present in the profile of children with dyslexia. Furthermore, controlling variables, although very important, excluding children with comorbidities also creates a less typical child profile. Many children with dyslexia experience several additional neurologically based brain differences. To exclude them from these studies, potentially idealizes the results. Based upon the size, constructs, and research designs of these studies, generalizations can only be made with great caution. Researcher bias, convenience sampling, and a focus on quantitative measures leave out valuable qualitative understandings.

Conclusion

Although there has been a recent augmentation of research investigating how brain stimulation influences reading intervention programs for children with dyslexia, the results are not conclusive. Promisingly, there is potential of various forms of NIBS and TCS to change the neurophysiology of the brain with associated improved reading skills results in children that struggle with reading. Caution must be held, as most of the studies had specific limitations of small sample sizes and convenience sampling techniques and have a potential for profile bias and researcher bias to focus on this specialized population.

Moving forward, the development of large-scale longitudinal studies should be embarked upon. More consistent protocols for tDCS use of children must be established. Other forms of NIBS must also develop consistent protocols so that replication can occur. In short, the 19 reviewed studies show great promise and excitement to those with atypical neural activity and reading difficulties. As this research advances and slowly becomes embedded into educational and medical systems more children will be helped. Dyslexia is a condition that changes the trajectory of livelihood, prosperity, and health. It is an invisible disability with very visible consequences. But with attuned focus and commitment, research projects such as the ones contained in the review will offer hope to those effected by dyslexia.

This systematic review was focused on the research question as to whether different forms of brain stimulation for intervention in literacy development amongst children with dyslexia would have a positive effect. No causal relationships were established, but strong correlations between total time, duration/sessions and the excitation of hypoactive regions in the left hemisphere proved to show changes in neural activity. The use of pre and post-test interventions, alongside fMRI mapping showed definitive changes.

Larger sample size replication studies need to be performed in order to be generalized to child populations or at least to larger sets of children specifically with the learning profile indicating non-typical reading development. Interestingly across the studies, the left TPC, left auditory cortex, the visual cortices and left tactile sensory fields have been explored. Lacking in the research is deeper investigation of the ventral occipito-temporal cortex (ITG, VLPFC) and the dorsal pathway including the intraparietal sulcus (IPS). In both of these cases, NIBS and DCS are more difficult due to the proximity of other brain and body components and the depth of their location in the brain.

As we seek to have conclusive evidence, the combination of specific stimulation protocols, combined with specific reading interventions need to be coupled with functional neuroimaging to track neurophysiological changes in the brain. Although there are encouraging results noted across the studies, it is educated speculation that leads us to surmise that changes within the brain structure have occurred when improvements are maintained over time. Individual-level variability in reading intervention programs has attracted neuroscience researchers' attention in recent years. Understanding the brain's function and how it differs between typically developing readers and atypical readers, such as those with dyslexia, is critical.

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APPENDIX

Table1.

Transcranial Brain Stimulation Studies on Children / Adolescents with Dyslexia / Learning Disability – Reading

Author	Design (Control Condition)	N	Mean age +/ SD (Age Range)	Form of Stimulation	Target Electrode Site/location of stimulation	Return electrode site/electrode size AND intensity or fMRI information	Duration	Polarity	Major Findings
Costanzo et al. (2019)	RCT double blind (sham controlled) Convenience Sample	26	13. 2 +/- 2. 4 (10-17)	tDCS	Left parietotemporal (mid P7-TP7)	Right cathodal parieto temporal / 5 x 5cm 1mA	18x20 min Over 6 weeks	Anodal/ cathodal	Improved non-word and low frequency word reading compared to sham control for 6 months. Long lasting improvement. Effect size 2. 5 (p=0. 01)
Lazzaro et al. (2021a)	RCT double blind (sham controlled)	26	13. 8 +/-2. 3(10. 8- 17. 8)	tDCS	Left TPJ (between P7-TP7)	Right TPJ (between P8-TP8)/5x5cm 1mA	18x20 min Over 6 weeks	Anodal/ cathodal	Anodal left cathodal right TPJ tDCS in active group improved reading fluency with simultaneous reading training
Lazzaro et al. (2021b)	RCT single blind (no sham)	10	13. 89 +/-2. 4 (10.8-16.7)	tDCS	Left TPJ (between P7-TP7)	Right TPJ (between P8-TP8)/5x5cm 1mA	20 min	Anodal/ cathodal	Anodal Left Cathodal right TPJ better text reading accuracy, speed, word recognition and modified attentional focusing
Rahimi et al. (2019a)	RCT single blind (sham controlled)	17	10. 35 +/- 1. 36 (9-12)	tDCS	Bilateral STG (T7,T8) Left STG (T3,T4)	Right shoulder/5 x 5 cm 1mA	20 min (3 single sessions)	Anodal	Measured Auditory processing and ERP. Improved visual attention processing in active tDCS vs control
Rahimi et al. (2019b)	RCT single blind (waitlist control)	45 (3x15)	9-12 M= 10. 35 +/- 1. 23	tDCS	Left dIPFC	NR/5x5 cm 1. 5 mA	10 x 20 min (daily)	Anodal	Left dIPFC tDCS showed improved visual attention processing in active tDCS vs cotrol
Rios et al. 2018	Open-label (no control group), blind statistical analysis	12	8-17 12. 5 +/- 3. 18	tDCS	2 mA Left middle temporal (T3) and superior temporal gyrus (T5)	Right supraorbital region (FP2)	5 consecutive days x 30 mins.	Anodal	Statistically significant increase in correct answers for nonwords and text tasks after day 5 (P=. 035 and P = . 012)
Rufener, Krauel, Meyer, Heize, and Zaehle (2019)	Single Blind with sham control	15 teens /15 adults not used	10-16 M= 13. 33 +/- 1. 94	tACS/ tRNS	L/R Auditory Cortex – offline gamma tACS at 40 Hz for 20 minutes; Offline tRNS (100-640 Hz)	EEG showed stimulation altered P50-N1 complex (auditory processing)	Single session, 20 minutes	Bilateral 40 H tACS left auditory cortex	Increased phoneme categorization and changes in auditory processing centre.

Table2.

Non-Invasive Brain Stimulation in Children and Adolescents with Dyslexia or Learning Disability- Reading

Author	Design (Control Condition)	N	Mean age +/-SD (Age Range)	Form of Stimulation	Region of Stimulation	Target of intervention	Time	Major Findings
Caldini et al. (2020)	2 groups randomly assigned blind groups with parent consent (Dyslexic with training; no training group) One -way ANOVA design.	25 per group N=50	7. 8 – 12 yrs.	Visual and Attention Cortices, cortical mechanisms	Oculomotor	Visual attention training to improve reading	Pretest, 10 minute visual attentional training of oculomotor tasks (saccades, pursuit movement, searching tasks)	Children with oculomotor training read faster in the post test and their fixation time was shorter than in pre-test. Concluded that visual attention training partially mitigated immature cortical structures responsible for saccades triggering.
Cancer et al., 2020	2 subgroups pseudo randomly assigned (but group similar)	12 x 2	8-14 yrs M=9. 79 SD = 1. 64	vHHS+AVG; RRT (auditory stimulation)	Oculomotor, visuo-spatial attention, auditory processing	vHHS and AVG vs. Rhythmic Reading Training. Intervention: sublexical treatment with rhythm processing and speed combined visual cue.	2x 45 min/day for 9 days over a 3-week period.	RRT improved pseudoword reading and speed associated with phonological awareness; vHSS and AVG more effective in increasing general reading accuracy with is associated with rapid automatized naming. AVG improved speed.
Cancer et al. 2021	2 groups; stratified sampling by matching age, sex, TIQ, reading baseline. (1 in-person, 1 virtual)	15 x 2	8-13 M=9. 8 SD= 1. 31	Visual and auditory stimulation; speed increased once 90% accuracy	Visual and auditory processing systems	Auditory processing, visual cortex	10 biweek lyx45mins. (Total 7.5 hours)	Used a mixed factorial ANOVA 2x2 analysis. Rhythmic Reading Training was equally effective in-person and virtually (η2 = 0. 02). Improved reading and rapid automatized naming. Visuo-spatial and attentional stimulations found significant effect on pseudo-word reading speed. Limitation lack of follow-up measures.
Cancer et al. (2022)	3 groups a) RRT + vHHS b) RRT c) control. Used one-way and multifactorial ANOVA	58	8-14 yrs. M=10. 8 SD= 1. 64	Rhythmic Reading Training; RRT + visual cue	Auditory temporal processing; visual attentional processing	Multisensory integration and cross-modal learning	10 x 45 minute s over 5 weeks	Significant immediate and medium term (3 months post intervention) effect using Rhythmic Reading Training. Pre and post measures looking at reading accuracy and fluency. Improvements of RAN, phonological, rhythmic and attentional abilities. No impact when combined with visual cueing.

Franceschini & Bertoni (2019)	Convenience sample. No control. No blind.	1B	HL 8. 9-13. 2 9. 79 SD 1. 33; LL 9. 42 SD 1. 19	AVG	Visual and auditory processing systems	Multi-sensory attentional network (magnocellular-dorsal pathway)	12 x 60 mins. Within 2 weeks	Those participants that improved their scores the most in games (High Learners/ HL) had better reading improvement from pre and post assessments than Low Learners (LL). Visual attention training showed improved in reading intervention programs. HL showed 1 year's spontaneous reading speed development (12 hours of intervention and no increase of error rate).
Helland et al. (2018)	Convenience sample, plus 2 controls – one with training, one without. One way ANOVA design.	47 (15 control training; 16 control no training; 16 Dyslexic)	8 yrs. CnT m= 8. 22 (SD .32) CT = 8. 23 (SD= .24) DT 8. 78 (SD= .26)	Auditory stimulation Dichotic listening taps	Auditory processing systems	Attentional network-interstimulus interval 4 ms	Trainin g 1x 5 consec utive days; post test 1 week later.	Dichotic listening results varied across 3 groups. Control no training (CnT)had little change. Changes in all measures for control training (CT) and some for Dyslexia Training (DT). Weaker attention scores for DT but improved RAN and DS scores not explained by test-re-test effect. 10 of 16 subjects showed improvement in attention shifting index (ASI). Study also confirmed that language processing skills and verbal working memory skills are related to focus and the ability to shift attention.
Koen et al. (2018)	Mixed design with intervention and delay intervention groups (no sham) Convenience Sample	15	14 +/-2 (8-19)	vHSS	Left superior temporal gyrus, IFG, LH IOT (VWFA)	Visual field stimulation	50 x 27 min	Determining L-type or P type or mixed DD changed area of stimulation. 67% achieved automatic processing and increased reading rate 20 words/minute
Lorusso et al. 2021	Mixed design, 6 groups, no shams. Repeated measures ANOVA analysis.	91 (54 male)	7-14 M=9. 44, SD 1. 41 Group 1 n= 27; <9years; Group 2 n=42 ages 9 & 10; Group 3, n= 22; 11 years+	AVG/vHSS	One visual hemisphere (based on Dyslexic type); contralateral stimulation; central lateralized stimulation and inter hemispheric integration	peripheral processing and global perception of stimuli moving at high speed and that are spatial temporally unpredictable	4 weeks (4-5 x a week for 20 – 30 mins.) Total of 14 hours	Based on Bakker's Balance Model, the Tachidino program (visual tachistoscopically presented words/nonwords with auditory stimuli) was found to have positive impact overall on reading speed, reading accuracy and writing ability. Children with most severe impairment had the strong improvement overall. Youngest participants showed greater improvement and was maintained in writing accuracy gains. ANOVA, power of 0.8 (acceptable).

Peters, Crewther, Murphy & Bavin (2021)	AVG-regular, AVG enhanced, control (double blind, with control)	64	8-13 M= 10. 37 +/_	vHSS	Visuo temporal processing	Attentional focus and rapid attention processing	10 x 30 min	Using Action Video Games (AVG) improved rapid naming and visuo temporal processing compared to control. Participants with low contrast magnocellular temporal processing improved most.
Van der Lubbe, Kleine & Rataj (2019)	Single blind with control; MANOVA design	26, 12 DD, 14 control	16 – 24 (20. 4 years for control, 23. 3 yrs. for DD)	vHSS	LPS and HPS on LH and RL. Passive Ag/AgCl ring electrodes 10-20 system at 61 locations. hEOG and vEOG measured on left and right eyes	Reaction times (RT) recorded in Spatial Frequency (LSF or HSF) on stimulus sides and response sides (Left or right)	1 hour	Results showed at end of cue-target interval no clear contralateral reduction of attention in upper alpha band. Noted slower responses than control especially in high spatial frequency targets in left VF. Dyslexics difficulty and sustaining attention. Dyslexic students better at Balloon tasks without controls. No difference found between executive functions, visual perception, and vigilance. Dyslexics student had faster responses for Low Spatial Frequency than HSF
Werth (2021)	Convenience sample. Control group of typical readers and control group of reading without computer aided pace.	60 + controls	8-15 m=10. 2 years; SD +/-1. 6	vHSS	L TPC, visual processing cortex	Diagnostic established 95% reading accuracy level for pseudowords. Child looked at affixation mark before each word. The complexity of the pseudowords was lessened with more time to view the word to find the teaching level for the child.	30 minute training, then computer altered the program to match child's needs 30 mins.	C omputer aided readings (pacing the amount of time the eye should spend on a 2 or 3 letter word segment in a pseudoword) showed drop of 69. 97% of reading mistakes. Cohen d=2. 649. No evidence that dyslexia was due to lack of eye movement control or reduced visual attention. Typical readers had increased errors when only able to see the words in segments.