Using fNIRS to Examine the Impact of Skill and Goal-Based Training on Resting State Functional Connectivity in Adults with Dyslexia

by

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Abstract

Dyslexia is a lifelong reading disability characterized by poor spelling and decoding abilities, and difficulty in word recognition. Studies on the neurobiological mechanisms of dyslexia and related intervention programs are prevalent. However, as the majority of these studies are conducted with children, little is known about the plasticity and functional connectivity in the brain of an adult with dyslexia. Methods. The current study addressed this gap by analyzing resting state functional connectivity (RSFC), via functional near-infrared spectroscopy, in a group of adults with dyslexia (N = 25), both before and after administration of a skill (N = 13) or psychosocial-based (N = 12) remediation program. The bilateral superior temporal gyrus and the bilateral fusiform gyrus were selected as seed regions to explore connectivity. Results. Compiled group data revealed a significant increase in resting state connectivity for seven channels within the left based reading network, and 2 additional channels in the right hemisphere. Across training groups, 3 regions of interest showed a significant increase in resting state functional connectivity following the 8 week goal-based remediation program, while the skill-based program has increased resting state functional connectivity in only one region of interest (left fusiform gyrus). Conclusion. Both literacy and psychosocial-based training programs can induce brain changes (as measured by functional connectivity) in the brain of adults with dyslexia. These findings highlight the importance of developing diverse and accessible remediation programs to support cognitive and functional brain changes in adults with dyslexia, potentially improving their quality of life and social integration.

Preface

This thesis is an original work by Madilyn Orchard. No part of this thesis has been previously published. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "Impact of training programs on brain and behaviour in adults with reading difficulties", Pro00110746, approved 10/12/2021.

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1. Introduction

Developmental dyslexia, a condition marked by challenges in reading despite adequate levels of education, motivation, and intelligence, poses a significant hurdle to individuals impacted by this disorder (Démonet et al., 2004). Dyslexia impacts around 7% of the global population, as reported by Yang and colleagues (2022). In addition to reading difficulties, children with dyslexia also experience significant and persistent challenges in spelling, which often remains the most prominent symptom of dyslexia in adulthood (Connelly et al., 2006; Lefly & Pennington, 1991). In addition to its impact on reading and writing, dyslexia can also result in adverse consequences in academic, social, and emotional aspects (Livingston et al., 2018). Neurobiologically, dyslexia manifests as a dysfunction in the left hemisphere language network, which is highly active and specialized in skilled readers (Schlaggar & Church., 2009; Richlan et al., 2009; 2011; Cattinelli et al., 2013; Kronbichler & Kronbichler., 2018). The current consensus is that both children and adults with dyslexia exhibit decreased activity and disrupted functional connectivity among crucial language-related regions, including the left fusiform gyrus and temporo-parietal junction (Pugh et al., 2000; Shaywitz, Lyon, & Shaywitz, 2006).While numerous remediation interventions have shown promise in enhancing reading skills and inducing corresponding changes in brain activity, the majority of these studies focus on very young populations. Considerably less is known about how these reading-related regions operate within a reading network in adults with dyslexia, and whether the networks are modified following intensive treatment. The work presented here aims to bridge this knowledge gap by examining the resting state functional connectivity patterns in adults with dyslexia before and after the implementation of intensive reading training programs.

2. Background

2.1 Neural Underpinnings of Dyslexia

Dyslexia, a persistent neurological disorder, manifests as difficulties in reading and spelling despite adequate intelligence and education levels, as well as intact sensory abilities (Lyon, Shaywitz, & Shaywitz, 2003). The brains of individuals with dyslexia exhibit notable functional differences compared to proficient readers. Individuals with dyslexia exhibit reduced activity in left-based reading regions, such as the left fusiform gyrus, left superior temporal gyrus, and left supramarginal gyrus (Pugh et al., 2000). Additionally, increased activation may also occur in right hemispheric structures and subcortical regions like the caudate and putamen, which has been referred to as compensatory activation (Pugh et al., 2000; Shaywitz et al., 2002).

2.2 Role of the Superior Temporal Gyrus (STG) in Dyslexia

Substantial evidence supports the involvement of the STG in dyslexia (Braid & Richlan, 2022; Dole et al., 2013; Joo et al., 2021; Richlan, 2012; Yan et al., 2021). One meta-analysis identified notable reductions in brain volume among individuals with reading impairments compared to those without, particularly in the left superior temporal sulcus and left superior temporal gyrus, which were also linked to functional differences (Richlan et al., 2013). Similarly, a meta-analysis by Eckert et al. (2016) emphasized significant volume differences in the left superior temporal sulcus and the left orbitofrontal gyrus as key areas of divergence between individuals with and without reading impairments. These structural differences extend into functional differences. For example, in comparison to proficient readers, individuals with dyslexia exhibit challenges in integrating visual and auditory information (Ye et al., 2017). The superior temporal gyrus has been identified as a crucial player in audiovisual speech integration, as indicated by Ye et al. (2017) who reported that skilled readers display heightened activation in the superior temporal gyrus when exposed to combined audiovisual stimuli, contrasting with auditory or visual stimuli alone. However, such an effect was absent in dyslexic readers. These findings imply that dysfunction in the left superior temporal region might contribute to some of the reading difficulties observed in individuals with dyslexia. It should be noted that most studies in these meta-analyses focused on children, highlighting a gap in the research. While the body of research on adults is expanding (e.g., Casanova et al., 2010; Frye et al., 2010; Pernet et al., 2009; Richardson et al., 2011; Steinbrink et al., 2008), we remain in the 'information gathering' phase.

2.2 Role of the Fusiform Gyrus (FG) in Dyslexia

Proficient readers are able to effortlessly integrate groups of letters into visual percepts. This word encoding process is pivotal for achieving fluency in reading, with the fusiform gyrus being identified as a key player in this mechanism (Mcandless et al., 2003). Researchers propose that dyslexic readers exhibit diminished integration and activation of the fusiform gyrus during reading compared to their skilled counterparts (Mcandless et al., 2003). A specific segment of the left fusiform gyrus is believed to hold a critical role in this process, being particularly responsive to visual words (Mcandless et al., 2003). This cortical region has been demonstrated to activate in response to word recognition while remaining unresponsive to individual letters and non-words (Cohen & Dehaene, 2004; Cohen et al., 2002). Lesions affecting the fibers connecting visual brain regions to the left fusiform gyrus have resulted in impaired rapid and fluid word reading, a condition termed word form dyslexia or letter-by-letter reading impairment (Molko et al., 2002). Studies involving dyslexic adults indicate that, unlike proficient readers, the fusiform gyrus does not exhibit increased activity in response to word forms (Mcandless et al., 2003). This evidence strongly suggests that the fusiform gyrus plays a substantial role in fluent reading ability, with impaired functionality observed in readers with dyslexia. The extent to which fusiform gyrus activity and connectivity can be modified following treatment remains underexplored in adults with dyslexia. The current study aims to address this gap by investigating changes in the fusiform gyrus, with respect to resting state functional connectivity after administration of skill and goal-based remediation programs.

2.4 Resting State Functional Near-Infrared Spectroscopy

Reading is an intricate cognitive process, involving the collaboration of various pathways distributed across different regions of the brain (Schurtz et al., 2015). Understanding the intricate interplay between these distant brain regions during reading processes, or at rest, requires a comprehensive approach. Resting state functional near-infrared spectroscopy (fNIRS) emerges as a powerful tool for investigating connectivity in a dyslexic brain.

Examination of fNIRS signals has uncovered temporal correlations between widely dispersed brain regions during the resting state. Resting state connectivity (RSC) is characterized by functionally connected brain regions displaying temporally correlated signals, in the absence of any specific tasks or stimuli (Schurz et al., 2015). It signifies consistent and repetitive co-activation of brain areas within an individual over time. Consequently, diminished RSC between brain regions suggests a lack of integration in cognitive processes, like reading (Dosenbach et al., 2007; Fair et al., 2007). Conversely, heightened resting state connectivity indicates a history of robust connections among cortical regions (Dosenbach et al., 2007; Fair et al., 2007). Resting state data, acquired without explicit tasks or stimuli, minimizes potential behavioral confounds, and thus the measured brain connectivity is presumably unaffected by individual differences in processing strategies or performance. Hence, resting state functional near infrared spectroscopy emerges as an excellent imaging technique for studying intricate processes, such as those associated with reading and writing (Schurz et al., 2015).

2.5 Resting-State Functional Connectivity in Dyslexia

Resting state investigations with proficient readers have identified associations among reading-related brain structures, particularly within the left-hemispheric network, forming reading networks even during rest (Koyama et al., 2011, 2013). The researchers discovered that regions traditionally associated with reading, such as the left inferior frontal gyrus, left superior temporal gyrus, and left fusiform gyrus, exhibited strong intrinsic functional connectivity even when participants were at rest. These findings suggest that the brain maintains a default network for reading that is functionally active even without explicit task engagement. This resting-state connectivity could serve as a baseline to compare with dyslexic populations, where altered connectivity patterns might reflect neuroplastic changes due to compensatory mechanisms or the effects of remediation programs. Understanding these baseline connections is crucial for interpreting how skill-based and psychosocial interventions could reorganize these networks to improve reading abilities in adults with dyslexia (Koyama et al., 2010). While resting state connectivity holds promise for neural dyslexia research, evidence from this approach is limited, with existing studies predominantly involving children.

Scurtz and colleagues (2015) examined resting state and task-based data from dyslexic adolescents aged 16 to 20. Notably, they reported diminished connectivity between areas associated with the left-hemispheric reading network. More specifically, they found that compared to non-impaired readers, dyslexic readers show reduced resting state connectivity between left posterior temporal areas associated with the left-hemispheric reading network, including the left fusiform gyrus and the superior temporal gyrus. This reduced connectivity pattern persisted during silent reading and a phonological lexical decision task, highlighting disruptions in pathways linked to the typical left-reading network in dyslexic readers.

In a study by Horowitz-Cross and colleagues (2015a) on children aged 8 to 10 with reading difficulties, a resting state functional connectivity analysis was conducted both before and after a 4-week reading acceleration training program (RAP). Post-training, improvements in word and nonword reading scores, reading fluency, and overall comprehension were observed, suggesting that successful training programs can positively impact cognitive functioning and connectivity. The results of this study demonstrate that this increase in reading ability was accompanied by increased resting state functional connectivity between the fusiform gyrus and other language components in children with reading difficulties. Another study by Horowitz-Cross et al. (2015c) explored connectivity in the fusiform gyrus in impaired and non-impaired readers aged 8 to 12 undergoing reading training. The results indicated improved reading scores and executive functioning in both groups, correlating with heightened activation and resting state functional connectivity between the anterior cingulate cortex, cingulo-opercular cognitive-control network, and the fusiform gyrus. Overall, these studies suggest that reading interventions can lead to measurable changes in both cognitive outcomes and the functional connectivity of brain regions associated with reading, demonstrating the brain's capacity for plasticity in response to targeted training. These findings support the idea that literacy-based training induces plasticity within reading-related neural networks even at rest

The functional connectivity of the reading network has been explored in various reading tasks (Schurz et al., 2015; Shaywitz et al. 2003; van der Mark et al. 2011), but few studies exist studying resting state in the neural networks underlying dyslexia in adults. Studying resting-state functional connectivity (RSFC) has been proposed as a promising method, unaffected by specific task demands or cognitive processing strategies (Cross et al., 2021). Compared to other neurological disorders, there are relatively few RSFC studies on dyslexia (Kronbichler & Kronbichler, 2018). The current resting state studies in dyslexia reveal reduced connectivity within the left-hemispheric reading network, affecting crucial regions like the fusiform gyrus and superior temporal gyrus (Schurz et al., 2015). Interestingly, interventions, such as reading training programs, show promise in restoring connectivity, suggesting the potential for neural plasticity even in the absence of explicit reading tasks (Horowitz-Cross et al., 2015a; Horowitz-Cross et al., 2015c). In summary, functional connectivity studies emphasize the crucial role of cortical connectivity in the reading network, and this study aims to contribute novel insights by utilizing fNIRS, an unexplored method in the context of RSFC in reading-related regions.

2.6 Reading Remediation: Current Evidence

2.61 Skill-based remediation. There is much evidence that literacy challenges persist into adulthood for individuals with dyslexia (Boets et al., 2013; Bruck, 1993; Cheema et al., 2023; Cheema et al., 2022; Cummine et al., 2020; Kemp et al., 2009; Law et al., 2015; Manis et al., 1990; Maughan et al., 2009; Pennington et al., 1986; Siegel et al., 1995; Tops et al., 2012; Wilson & Lesaux, 2001). Traditionally, effective remediation approaches have been designed for children, focusing on phonological processing, print awareness, morphological understanding, and reading fluency. The applicability and efficacy of these skill-based interventions for adults remain under-explored. In Canada, adult literacy programs such as AlphaRoute, which operated from 1996 to 2011, employed a blended learning model incorporating both in-person and online components, with individualized student learning plans (UNESCO, n.d.). Despite its initial success, the program faced challenges due to rapid technological advancements and evolving user expectations, ultimately leading to its discontinuation. Current offerings like those from United for Literacy (https://www.unitedforliteracy.ca) and the UNESCO Institute for Lifelong Learning (https://uil.unesco.org/literacy) provide online literacy training but lack systematic measurement of reading performance improvements and tailored strategies for adults with lifelong literacy difficulties.

Skill-based training for adults with dyslexia have the potential to demonstrate several strengths. These programs focus on specific reading skills, such as which can improve reading fluency and comprehension (Layes et al., 2022). Programs often incorporate evidence-based practices, making them potentially effective for enhancing reading skills (Al Otaiba et al., 2023). However, limitations persist. Skill-based interventions may not address the broader psychosocial challenges associated with dyslexia, such as self-esteem and emotional well-being. Additionally, the transferability of skills learned in training to real-world reading contexts might be limited, especially if the training does not integrate practical, everyday reading tasks. The lack of adaptation in these programs for adult learners' unique needs further restricts their overall effectiveness.

2.62 Goal-based remediation. Recent research has supported the notion that goal-based remediation strategies for dyslexia may be a useful avenue of treatment. This perspective aligns with the principles of the social model of disability, which was developed as a response to the limitations of the medical model. Unlike the medical model, which focuses on individual deficiencies, the social model emphasizes the role of societal barriers in creating disabilities (Haegele & Hodge, 2016). It distinguishes between impairment, which refers to physical or psychological conditions (Forhan, 2009; Goodley, 2001; Withers, 2012), and disability, defined as the disadvantages imposed by social, cultural, economic, and institutional barriers (Goodley, 2001; Haegele & Hodge, 2016; Macdonald, 2009). In the context of reading impairments, this model suggests that addressing external barriers and focusing on achievable goals may be more effective than pathologizing the individual. By shifting the emphasis from the individual to the broader societal context, goal-based remediation strategies could help reduce the disabling effects of dyslexia, making it a promising approach in treatment.

The existing evidence for goal-based remediation in children is promising, with many studies reporting notable improvements in psychosocial outcomes (such as self-esteem and emotional well-being) and reading skills, including decoding, fluency, and comprehension, for children with dyslexia (Aro et al., 2018; Lovett et al., 2021). These findings underscore the potential effectiveness of psychosocial interventions in this population. In contrast, only a handful of studies have investigated the impact of psychosocial interventions on adults with dyslexia. These studies have primarily focused on outcomes like self-esteem, verbal memory (Jensen et al., 2000), executive functioning, and emotional regulation (Nukari et al., 2020; 2022). However, these psychosocial aspects are often minor components of broader skill-focused programs. As a result, the specific effects of targeted psychosocial training on enhancing psychosocial outcomes in adults with dyslexia remain largely unknown.

One of the significant advantages of goal-based remediation is its potential to be more accessible and adaptable for adults with dyslexia compared to traditional skill-based methods. Goal-based approaches are inherently flexible, allowing adults to set and pursue personal and professional objectives that align with their unique needs and circumstances. This flexibility can accommodate varying schedules, learning styles, and life responsibilities, which are often more pronounced in adults than in children. Furthermore, by emphasizing practical goals and real-world applications, goal-based strategies can integrate seamlessly into daily life, potentially enhancing engagement and motivation.

3. Thesis Statement

The current study aims to assess the impact of literacy training programs (both skill and goal-based) on resting state functional connectivity (RSFC) of reading related regions, in adults with dyslexia. Namely, does the RSFC of the bilateral superior temporal gyrus and fusiform gyrus increase as a result of training?

Research Question 1 - What is the impact of literacy remediation on RSFC?

Hypothesis 1.1: We anticipate that we will see increased functional connectivity associated with the left STG and FFG following remediation.

Hypothesis 1.2: We anticipate that we will see decreased functional connectivity associated with the right STG and FFG following remediation, indicative of compensatory mechanisms reorganizing back to the left hemisphere following remediation.

Research Question 2 - Does RSFC change as a function of skill vs. goal based literacy remediation?

Hypothesis 2.1: We anticipate participants undergoing skill-based literacy remediation will show increased functional connectivity associated with the left STG and FFG following remediation, and decreased functional connectivity associated with the right STG and FFG. This hypothesis is based on the premise that skill-based interventions, which focus on specific literacy skills, will more directly target and enhance connectivity in the traditional left-hemispheric reading network, especially in regions known to be underactive in individuals with dyslexia.

Hypothesis 2.2: We anticipate participants undergoing goal-based literacy remediation will show increased functional connectivity associated with the left STG and FFG following remediation, and increased functional connectivity associated with the right STG and FFG. This hypothesis is founded on the idea that goal-based interventions, which focus on broader psychosocial strategies and compensatory mechanisms, may encourage more distributed and bilateral connectivity changes across the reading network, reflecting adaptive neural responses to a less targeted but more holistic approach to remediation.

4. Experimental Design and Methods

4.1 Participants and Training Programs

As part of a larger study, skill and goal- based intervention programs were administered to a group of 25 adults with dyslexia (mean age= 31.74 years, number of female participants = 17, number of right handed participants = 25) . All participants were randomly assigned to either the skill or goal-based training groups, with 13 participants in the skill-based group and 12 participants in the goal-based group. Inclusionary criteria included having English as their primary language, in addition to having a self reported reading disability, and a score of 1.5 standard deviations below a skilled reading group on a reading measurement given before training. Exclusionary criteria included a history of vision or hearing impairments, or a prior neurological disorder diagnosis such as attention deficit hyperactivity disorder or stroke.

Training for both groups lasted for an eight week period. Out of the 25 participants, pre and post resting state fNIRS data was collected for only 20 of the participants (10 participants in the skill based group, and 10 participants in the goal based group). The remaining 5 participants were removed from this study as they did not complete the training program or return to the lab for the post training fNIRS data collection session.

4.11 Remediation programs

Skill-based. The skill-based training group focused on structured literacy enhancement through a series of carefully designed modules. After the pre-intervention session, participants received a website link and detailed instructions on accessing the training platform, including guidance on the frequency of training and basic login procedures. The training was divided into four modules—sound awareness, print awareness, meaning awareness, and reading fluency—each spanning two weeks. Participants were required to log in weekly to complete video lessons and assignments, which were the core components of the intervention. The intervention was designed to provide approximately 50-60 minutes of training per week, including 20-25 minutes for video lessons, 10-15 minutes for assignments, and 5-10 minutes for weekly check-in meetings with a lab member. These check-in meetings were aimed at discussing the participant's progress, addressing any challenges faced, and providing feedback. This eight-week program was flexible, allowing participants to complete the training at their convenience, as long as the weekly requirements were met.

Goal-based. The goal-based training group was designed to be highly individualized, focusing on personal goals related to everyday literacy challenges faced by individuals with dyslexia. After the pre-intervention session, participants engaged in an online Goal Attainment Scaling (GAS) session conducted via Zoom. This session began with a goal-setting interview, where participants collaborated with interviewers to identify their most important goals. For each goal, a baseline was established at a -1 level, with subsequent attainment levels ranging from -2 (worst expected outcome) to +2 (best-expected outcome). Participants, along with the interviewers, brainstormed strategies and activities tailored to their interests, motivations, and life circumstances to achieve these goals. For example, a participant aiming to improve their ability to follow written instructions in a recipe might use strategies such as highlighting key steps and practicing reading comprehension by breaking down the recipe into smaller, more manageable sections. The intervention was also designed to provide approximately 50-60 minutes of training per week, each participant dedicated 40-50 minutes weekly to implementing these strategies, complemented by 5-10 minutes of check-in meetings to review progress and make adjustments as needed. Participants in this program each set 4 individual goals, with the training for each goal lasting two weeks.

4.12 Procedures

Once the participants were notified of their eligibility, an in-person data collection session was arranged to carry out the pre-intervention behavioral and neuroimaging assessments. During this session participants completed reading history questionnaires and consent forms. This session also encompassed 40 minutes of behavioral testing and an additional hour dedicated to neuroimaging testing. The behavioral testing included the following standardized tests:

1. The Sight Word Efficiency (SWE) subtest and the Pseudo-Word Decoding Efficiency (PDE) subtest of the Test of Word Reading Efficiency - 1st Edition (TOWRE) (Torgeson et al., 1999).
2. Word identification and Word Attack tests from Woodcock Reading Mastery tests-III (WRMT-III) (Woodcock, 2011).
3. Wide Range Achievement Test - 4th Edition (Wilkinson & Robertson, 2006) Spelling subtest.

4. Passage Comprehension from Woodcock Reading Mastery tests-III (WRMT-III) passage comprehension task (Woodcock, 2011).
5. A reading self-efficacy questionnaire modified from a reading self-efficacy questionnaire from the study by Carroll and Fox (2017) .
6. A reading anxiety questionnaire modified from a foreign-language anxiety scale (Saito, Garza, & Horwitz, 1999).
7. A reading motivation scale borrowed from Schutte and Malouff (2007).
8. At only the pre-intervention session, participants will complete a measure of nonverbal intelligence using the Matrix Reasoning test from the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999).

For the hour of neuroimaging tests, participants were measured and fitted for their fNIRS caps. In addition to collection of resting state data, participants also engaged in two additional tests to collect task-based data: the phoneme deletion task (Byrd, McGill, & Usler, 2015; Welcome, Leonard & Chiarello, 2010) and the sentence comprehension task borrowed from Dr. Chris Westbury's database of text repository (https://www.psych.ualberta.ca/~westburylab/downloads/wlallfreq.download.html). The post-intervention sessions mirrored the initial behavioral and neuroimaging tasks, in addition to including a survey to gather feedback on their respective programs.

4.2 fNIRS Data Collection

Resting state measurements were collected with the Brite24 Artinis device, using a sampling rate of 50Hz, and the wavelengths of 690 nm and 830 nm. The fNIRS caps were placed using the 10/20 positioning system, in which the position of the optodes is determined by the four standard positions of the head (nasion, inion, and the right and left preauricular points), to locate Cz. The fNIRS cap was fitted with 2 sets of 8 detectors and 10 emitters, for a total of 44 channels over the two hemispheres. The distance between the transmitters and receivers was 30 mm. Oxysoft version 3.2.51 (from Artinis) was used to collect the raw fNIRS data. During the eight minute period which resting state data collection occurred, participants were instructed to sit down, close their eyes, and not to think of anything specific.

4.3 Regions of Interest

The regions of interest included the bilateral superior temporal gyrus (STG) and fusiform gyrus (see Figure 1 for the exact optode pairing that corresponds to these regions). The left STG and left fusiform gyrus were chosen based on their involvement in normative reading processes, and the evidence suggesting that we may detect normalization changes in left-based reading structures after administration of a skill or goal-based training program. Whereas the right STG and right fusiform gyrus were chosen based on their involvement in compensatory reading processes, and the evidence suggesting that we may detect compensatory changes in right-based structures after administration of a dyslexia training program.

4.4 fNIRS Data Quality Check and Preprocessing

Prior to data preprocessing, quality analysis was conducted using the Quality Testing of Near-Infrared Scans (QT-NIRS) toolbox (Hernandez & Polloni, 2020). This toolbox calculates the scalp coupling index for every channel in the fNIRS data set. QT-NIRS assesses the quality of the signal based on the presence of heartbeat oscillation, which indicates good coupling between optodes and the scalp (Pinti et al., 2019). Any channel that did not meet the 0.5 quality threshold was removed prior to formal analysis. From the existing 20 participants with both pre and post-resting state data, an additional 2 participants were removed from both the left and right hemispheres analysis due to poor channel quality of regions of interest. Table 1 depicts a full list of the channels that were removed prior to formal analysis.

Resting state data was preprocessed using the NIRS-KIT (Hou et al., 2021), a MATLAB-based toolbox for fNIRS data analysis (Figure 2). During pre-processing, the first and last 15 seconds of the raw time series were removed to ensure a stable signal. Then, the data went through the following preprocessing steps. First, the raw data was detrended. To do this, a polynomial regression model was used to estimate a linear or nonlinear trend and subtract it from the raw hemoglobin concentration signal (Hou et al., 2021). Next, the temporal derivative distribution repair (TDDR) correction was used to correct for head motion (Fishburn et al., 2019). Finally, a bandpass filter with cut-off frequencies of 0.01 Hz and 0.08 Hz was used to reduce the physiological noise such as fluctuations from heart rate and breathing rate, and instrumental noise, respectively (Pinti et al., 2019). The remaining low-frequency fluctuations in this range have been suggested to reflect spontaneous neural activity, so they were noted to be of physiological importance during resting state analysis (Hou et al., 2021).

Regions of Interest. A customized probe setup file was generated using the Topomaker Module from the NIRS-KIT package. Figure 3 depicts the arbitrary probe and channel configuration used to analyze our data set. The channels corresponding to the left and right STG and FFG were selected and used as seed regions in the RSFC analysis.

4.5 Analysis

For each participant, at both pre and post-testing, individual-level seed-based functional connectivity was assessed by calculating the Pearson correlation coefficient between the time series of the fNIRS signal from the region of interest (ROI) and the time series from each of the other channels across the entire fNIRS dataset. This process generated a connectivity map for each participant, reflecting the strength of the temporal correlation between the seed region and all other measured brain regions (i.e., ROI2Whole FC analysis; Hou et al., 2021). These individual connectivity maps were then averaged into a group connectivity map for each seed region. For each group (skilled vs. goal) and each ROI (4: bilateral STG and bilateral fusiform gyrus), a paired t-test was used to determine whether the connectivity between pre and post-remediation was significantly different. A false discovery rate (FDR) correction approach was applied for each ROI to assess significance and minimize Type 1 error.

5. Results

5.1 Neuroimaging Results

Table 2 depicts the significant results of the paired t-test for both left superior temporal gyrus and the left fusiform gyrus. For the left superior temporal gyrus, our results indicate one channel with increased resting state functional connectivity in the RH inferior parietal (p=0.0350). We also found a significant increase in functional connectivity in 6 channels connected to the second region of interest, the fusiform gyrus. These increases were mainly focused to the bilateral parietal and left hemispheric occipital regions; p-values for these channels are located in Table 2. Table 3 depicts the significant results of the paired t-test for both the right superior temporal gyrus and the right fusiform gyrus. For the right superior temporal gyrus our results indicate two channels with increased resting state functional connectivity, one spanning to the RH inferior parietal region (p=0.0464), and the other spanning to the LH frontal region (p=0.0061). The right fusiform gyrus showed no channels with significant increases in resting state functional connectivity.

5.11 Research Question 2.

Next, we separated the participants based on the training program and reanalyzed the data. For the participants in the skill-based training programs, we found only one channel with significantly increased resting state functional connectivity spanning our four regions of interest. For the left fusiform gyrus, our results indicate one channel with increased resting state functional connectivity in the RH frontal region (p=0.0356) (table 4).

For the participants in the goal-based training programs, we found 4 channels with increased resting state functional connectivity spanning our four regions of interest. For the left superior temporal gyrus, our results indicate one channel with increased resting state functional connectivity in the LH superior frontal region (p=0.0258). We also found a significant increase in functional connectivity in 2 channels connected to the fusiform gyrus: RH occipital region (p=0.0015) and LH occipital region (p=0.0400). The last channels with increased RSFC spanned from the right superior temporal gyrus to the RH occipital region (p=0.0432), while there was no significant result for the right fusiform gyrus; p-values for these channels are located in Table 5.

5.2 Behavioral Results

Behavioral data was collected from all participants pre- and post-training to evaluate the impact of the skill-based and goal-based remediation programs. Paired t-tests were performed on the seven outcome measures outlined in the methods section, including real word and non-word reading fluency, word identification, word attack, spelling, passage comprehension, reading self-efficacy, reading anxiety, and reading motivation.

Significant improvements in real word reading fluency were observed in both the skill-based (p = 0.0036**) and goal-based (p = 0.0270*) groups, with participants showing faster reading times following training. The skill-based group increased their reading speed by an average of 0.23 words per second, while the goal-based group improved by 0.17 words per second. For non-word reading fluency, both the skill-based ($p = 0.0019$**) and goal-based ($p = 0.0058$**) groups demonstrated significant score increases, with mean reading speed increases of 0.15 and 0.14 words per second, respectively. In the word identification task, the skill-based group exhibited a significant improvement ($p = 0.0046$**), with a mean increase of 10.2 points, while the goal-based group also showed a significant gain ($p = 0.0091$**), with an increase of 11.3 points. Similarly, in the word attack task, the skill-based group improved significantly ($p = 0.0415$*), with an average increase of 8.1 points, and the goal-based group saw a significant rise ($p = 0.0130$*), with a 5.9-point increase. The spelling subtest showed significant improvements in both groups. The skill-based group demonstrated a notable enhancement in spelling ability ($p = 0.0799$*), with a mean score increase of 2.3 points, and the goal-based group improved significantly ($p = 0.0081$**), with a 4.7-point increase. Passage comprehension scores also improved significantly for both the skill-based ($p = 0.0205$*) and goal-based ($p = 0.0052$**) groups, with mean increases of 10.2 and 12.2 points, respectively.

No significant changes were observed in the reading self-efficacy scale for either group (skill-based group: $p = 0.2328$; goal-based group: $p = 0.1055$). Similarly, the reading anxiety scale did not show significant differences for either group (skill-based group: $p = 0.3845$; goal-based group: $p = 0.1151$). Lastly, the reading motivation scale revealed significant improvements in both groups, with the skill-based group demonstrating increased motivation to read ($p = 0.0150$*), and the goal-based group showing a similar enhancement ($p = 0.0352$*). Table 6 provides the mean scores and results of the paired t-test for all assessments.

6. Discussion

Here we set out to explore changes in resting state connectivity, following reading remediation, in adults with dyslexia. We found that connectivity between resting state activation of the bilateral fusiform gyrus and the bilateral superior temporal gyrus– along with other bilateral brain areas– were found to increase after administration of the 8 week reading remediation program. Neural plasticity is an important factor that reflects successful learning, and we provide evidence of plasticity in reading-related circuits for the participants in our study.

6.1 Implications for the Left Fusiform Gyrus

What is particularly notable, is that the current study found evidence of increased resting state functional connectivity between the left fusiform gyrus, and *six* other brain regions spread over the bilateral parietal and occipital lobes. This suggests that the eight week training program resulted in significant brain changes, resulting in both normalizing and compensatory patterns in our population of adults with dyslexia. The increased resting state functional connectivity between the fusiform gyrus and areas of the left hemispheric occipital and temporal lobes is indicative of a normalizing change, as this reflects baseline restoration of connections within the typical left-based reading network, which is specialized for reading (Kronschnabel et al., 2014). Additionally, increased functional connectivity between the left fusiform gyrus, and areas of the right parietal lobe, is indicative of a compensatory neurological change (Pugh et al., 2000). This change in connectivity reflects baseline strengthening of connections between brain areas outside of the typical left-based reading network, which may be compensating for lack of the typical left-hemispheric activation when reading.

Findings from this study are consistent with those from Horowitz-Kraus and colleagues (2015a), as they also found increased resting state functional connectivity with areas connecting to the left fusiform gyrus, after administration of their reading acceleration training program in a group of children with dyslexia. connectivity between visual and reading based brain regions, such as the fusiform gyrus.

Overall, we have observed plastic changes in resting state connections to the left fusiform gyrus, an area crucial for word encoding and word recognition, after administration of a eight week literacy and psychosocial based reading training program in adults with dyslexia. This data suggests that the increased performance on reading tasks observed from the participants in our study could be explained by the increases in functional connectivity between regions critical for word identification and word encoding, namely the fusiform gyrus.

6.2 Implications for the Left Superior Temporal Gyrus

As stated in the results, we found significant increased resting state functional connectivity between the left superior temporal gyrus and the left fusiform gyrus (discussed above) and the right parietal lobe. What is particularly noteworthy is the reduced number of connections associated with the STG (i.e., 1) in comparison with the FFG (i.e., 6). There are several potential regions for this discrepancies. First, the remediation program was primarily visual (as opposed to aural) in it's format, potentially increasing the reliance on the visual components of the reading network (i.e., FFG) as opposed to the auditory components of the reading network (i.e., STG). Alternatively, the reduced changes in connectivity associated with the STG may signify less ability to change (i.e., plasticity) compared to the FFG. However, the substantial literature reporting activity changes during task-based brain imaging studies, suggests that this is a less likely explanation. Ultimately, more work that explores the range of plasticity in adult brains, following remediation for dyslexia is warranted to better understand the contribution of these regions to behavioral changes in this population.

6.3 Implications for the Right Hemisphere

In contrast to the robust findings observed in the left hemisphere, our study found fewer significant changes in resting state functional connectivity in the right hemisphere following the 8-week reading remediation program for adults with dyslexia. This asymmetry aligns with the established literature, which emphasizes the dominance of the left hemisphere in reading-related tasks and the potential for compensatory mechanisms in the right hemisphere in dyslexia (Shaywitz et al., 2002). Despite the overall lower number of significant results, notable changes were observed. Specifically, we found increased resting state functional connectivity between the right superior temporal gyrus, and two channels spanning to both the left and right hemisphere. This pattern of connectivity suggests a compensatory mechanism, where the right hemisphere may be augmenting its involvement in visual processing and attentional control to support reading tasks. This interpretation is consistent with studies suggesting that individuals with dyslexia often exhibit enhanced reliance on right hemisphere regions to compensate for deficits in left hemisphere reading networks (Shaywitz et al., 2002). This finding may reflect a supplementary role of the right superior temporal gyrus in supporting visual and attentional processes during reading tasks in individuals with dyslexia. However, the fewer connections observed compared to the left hemisphere highlights potential differences in the neuroplastic response of the right hemisphere to remediation interventions.

The asymmetry in findings between the hemispheres underscores the specialized role of the left hemisphere in reading-related processes and the adaptive mechanisms occurring in the right hemisphere in dyslexia. Our results suggest that while the left hemisphere shows clear signs of normalization changes, the right hemisphere's responses are more indicative of compensatory activations. Future studies with larger sample sizes and longitudinal designs are warranted to further elucidate the dynamic interplay between hemispheric specialization and neuroplasticity in dyslexia remediation programs.

6.4 Implications for Group Differences in Training Approaches

Our study explored the differential impacts of two distinct reading remediation approaches —skill-based and goal-based training—on resting state functional connectivity (RSFC) in adults with dyslexia. The findings revealed that the goal-based training group exhibited more substantial increases in RSFC, with four channels of increased connectivity primarily located in the left hemisphere. In contrast, the skill-based training group showed increased RSFC in only one channel, also in the left hemisphere. This suggests that the goal-based training might be more effective in fostering neural changes associated with reading improvement in this population.

The significant improvements observed in reading speed, word identification, word attack, spelling, passage comprehension, and reading motivation following both skill-based and goal-based remediation programs offer important insights into the efficacy of these interventions for adults with dyslexia. These findings suggest that adults with dyslexia can benefit from targeted remediation programs aimed at improving literacy skills. Both types of programs facilitated substantial behavioral changes, though they impacted specific areas differently, pointing to their unique strengths and limitations.

6.5 Impact of Goal-Based Training

The significant outcomes observed in the goal-based training group may be attributed to several factors inherent in the intervention design. Unlike the skill-based intervention, which focused on explicit instruction of literacy skills (e.g., reading fluency, sound awareness, print awareness, and meaning awareness) through weekly online lessons and assignments, the goal-based intervention emphasized personalized goal setting related to self-efficacy, anxiety, and motivation in the context of everyday reading challenges. This approach likely engaged participants in a more integrative and self-directed learning process, fostering greater internal motivation and sustained engagement in the training activities. Research has shown that motivation-driven learning strategies can enhance neural plasticity in adults by promoting greater cognitive engagement and the recruitment of broader neural networks (Zhang et al., 2018).

The goal-based training demonstrated notable success in fostering improvements in both behavioral and motivational domains, suggesting a more effect on the participants' reading experience. Like the skill-based group, the goal-based group also showed significant gains in reading speed, word identification, and other literacy measures, This group also experienced significant increases in reading motivation. The goal-based training, with its emphasis on self-efficacy, anxiety reduction, and personalized goal setting, appears to have empowered participants to take greater ownership of their reading progress, leading to heightened motivation. However, similar to the skill-based training, the lack of significant change in reading self-efficacy and reading anxiety suggests that while participants became more motivated, they may still have experienced persistent challenges related to their confidence and emotional responses to reading.

6.6 Impact of Skill-Based Training

On the other hand, the skill-based training, while valuable in imparting foundational literacy skills, might have been less effective in promoting substantial changes in RSFC. The structured nature of this intervention, with its focus on discrete skills in isolation (e.g., reading fluency, sound awareness), may not have provided the same level of holistic engagement or emotional investment as the goal-based approach. Moreover, adults with dyslexia may benefit more from interventions that address their unique motivational and emotional needs, rather than traditional skill-based remediation alone. The single channel of increased RSFC observed in this group suggests that while some neural adaptations occurred, they were limited compared to those in the goal-based group. However, future studies with larger sample sizes are warranted to further confirm these findings.

Despite the limited RSFC results, the skill-based training demonstrated effectiveness in improving objective behavioural literacy measures. Participants in this group showed significant improvements in reading speed, word identification, and spelling, indicating that this structured, methodical approach effectively targeted the foundational components of reading. These results align with prior findings that phonological-based interventions can enhance reading abilities in individuals with dyslexia (Vender et al., 2022). However, while the skill-based training effectively improved literacy, it did not significantly affect reading self-efficacy or reduce reading anxiety. This suggests that while literacy gains were made, the psychosocial challenges often associated with dyslexia, such as anxiety and reduced confidence in reading, may require additional interventions focused on emotional and motivational aspects of learning.

7. Conclusions

This study provides evidence that effective training programs designed to enhance reading strategies in adults with dyslexia can increase functional connectivity in reading-related brain areas, detectable even at rest. The findings offer valuable insights into the neural pathways involved in reading abilities and disabilities. Importantly, this study also highlights the need for interventions tailored specifically to adults with dyslexia, as most research on reading intervention programs has focused on children. There is limited evidence supporting the effectiveness of similar programs in adults. However, our findings contribute to the growing body of evidence suggesting that adults can improve their reading abilities, demonstrating that it is never too late to engage in reading interventions. Additionally, this study provides evidence of neuroplasticity within reading-related networks extending into adulthood, a significant finding given that brain plasticity related to reading is less well-understood in adults than in children. Our results shed light on the timeline and neural mechanisms underlying reading-related plasticity in adulthood, expanding our understanding of how the adult brain can adapt to reading interventions.

8. Limitations

A major limitation of this study is the relatively small sample size, which was exacerbated by the challenges associated with fNIRS methodology (i.e., the exclusion of participants and individual channels from formal analysis). When we compiled participants across different groups for analysis, we observed more significant results. This is likely due to the larger combined sample size and potential practice effects from repeated reading tasks. However, this approach limits our ability to draw definitive conclusions about the effectiveness of the individual goal- and skill-based programs. To more robustly assess these programs, future research should aim to include a larger number of participants in each group, allowing for more reliable and valid comparisons of program outcomes.

8. References

Al Otaiba, S., McMaster, K., Wanzek, J., & Zaru, M. W. (2023). What we know and need to know about literacy interventions for elementary students with reading difficulties and disabilities, including dyslexia. *Reading Research Quarterly*, *58*(2), 313-332.

Aro, T., Viholainen, H., Koponen, T., Peura, P., Räikkönen, E., Salmi, P., Sorvo, R. & Aro, M. (2018). Can reading fluency and self-efficacy of reading fluency be enhanced with an intervention targeting the sources of self-efficacy? Learning and Individual Differences, 67, 53-66. doi:https://doi.org/10.1016/j.lindif.2018.06.009

Braid, J., & Richlan, F. (2022). The functional neuroanatomy of reading intervention. *Frontiers in Neuroscience*, *16*, 921931.

Bruck, M. (1993). Component spelling skills of college students with childhood diagnoses of dyslexia. Learning Disability Quarterly, 16(3), 171-184. https://doi.org/10.2307/1511325

Boets, B., Op de Beeck, Hans P., Vandermosten, M., Scott, S. K., Gillebert, C. R., Mantini, D., Bulthé, J., Sunaert, S., Wouters, J & Ghesquière, P. (2013). Intact but less accessible phonetic representations in adults with dyslexia. Science, 342(6163), 1251- 1254. https://doi.org/10.1126/science.1244333

Burton, M. W. (2001). The role of inferior frontal cortex in phonological processing. *Cognitive Science*, *25*(5), 695-709.

Byrd, C. T., McGill, M., & Usler, E. (2015). Nonword repetition and phoneme elision in adults who do and do not stutter: Vocal versus nonvocal performance differences. Journal of Fluency Disorders, 44, 17-31. https://doi.org/10.1016/j.jfludis.2015.01.004

Carroll, J. M., & Fox, A. C. (2017). Reading self-efficacy predicts word reading but not comprehension in both girls and boys. Frontiers in Psychology, 7(2056), 1–9.

https://doi.org/10.3389/fpsyg.2016.02056

Cattinelli, I., Borghese, N. A., Gallucci, M., & Paulesu, E. (2013). Reading the reading brain: a new meta-analysis of functional imaging data on reading. Journal of neurolinguistics, 26(1), 214-238.

Cheema, K., Fleming, C., Craig, J., Hodgetts, W. E., & Cummine, J. (2023). Reading and spelling profiles of adult poor readers: Phonological, orthographic and morphological considerations. *Dyslexia*, *29*(2), 58-77.

Cheema, K., Cassidy Fleming, J. C., Hodgetts, W. E., & Cummine, J. (2022). Reading and Spelling Profiles of Adults with and without Developmental Dyslexia: Phonological, Orthographic and Morphological Considerations. *Investigating the Behavioral and Neural Impact of Skill and Goal-based Interventions in Adults with Dyslexia*, 26.

Cohen, L., Dehaene, S., Naccache, L., Lehéricy, S., Dehaene-Lambertz, G., Hénaff, M.-A., & Michel, F. (2000). The visual word form area. Brain, 123(2), 291–307. https://doi.org/10.1093/brain/123.2.291

Connelly, V., Campbell, S., MacLean, M., & Barnes, J. (2006). Contribution of lower order skills to the written composition of college students with and without dyslexia. *Developmental neuropsychology*, *29*(1), 175-196.

Cross, A. M., Ramdajal, R., Peters, L., Vandermeer, M. R., Hayden, E. P., Frijters, J. C., ... & Joanisse, M. F. (2021). Resting-state functional connectivity and reading subskills in children. *Neuroimage*, *243*, 118529.

Cummine, J., Villarena, M., Onysyk, T., & Devlin, J. T. (2020). A study of null effects for the use of transcranial direct current stimulation (tDCS) in adults with and without reading impairment. *Neurobiology of Language*, *1*(4), 434-451.

Dehaene, S., & Cohen, L. (2011). The unique role of the visual word form area in reading. Trends in Cognitive Sciences, 15(6), 254–262. https://doi.org/10.1016/j.tics.2011.04.003

Démonet, J. F., Taylor, M. J., & Chaix, Y. (2004). Developmental dyslexia. *The Lancet*, *363*(9419), 1451-1460.

Dole, M., Meunier, F., & Hoen, M. (2013). Gray and white matter distribution in dyslexia: a VBM study of superior temporal gyrus asymmetry. *PloS one*, *8*(10), e76823.

Dosenbach NU Fair DA Miezin FM Cohen AL Wenger KK Dosenbach RA Fox MD Snyder AZ Vincent JL Raichle ME et al. 2007. Distinct brain networks for adaptive and stable task control in humans. *Proc Natl Acad Sci USA*. 104:11073–11078.

Eckert, M. A., Berninger, V. W., Vaden, K. I., Gebregziabher, M., & Tsu, L. (2016). Gray matter features of reading disability: a combined meta-analytic and direct analysis approach. *ENeuro*, *3*(1).

Fair, D. A., Dosenbach, N. U., Church, J. A., Cohen, A. L., Brahmbhatt, S., Miezin, F. M., ... & Schlaggar, B. L. (2007). Development of distinct control networks through segregation and integration. *Proceedings of the National Academy of Sciences*, *104*(33), 13507-13512.

Fishburn FA, Ludlum RS, Vaidya CJ, Medvedev AV. Temporal Derivative Distribution Repair (TDDR): A motion correction method for fNIRS. Neuroimage.

Forhan, M. (2009). An analysis of disability models and the application of the ICF. *Disability and rehabilitation*, *31*(16), 1382-1388.

Goodley, D. (2001). 'Learning difficulties', the social model of disability and impairment: challenging epistemologies. *Disability & Society*, *16*(2), 207-231.

Guyer, A. E., Pérez‐Edgar, K., & Crone, E. A. (2018). Opportunities for neurodevelopmental plasticity from infancy through early adulthood. *Child development*, *89*(3), 687-697.

Haegele, J. A., & Hodge, S. (2016). Disability discourse: Overview and critiques of the medical and social models. *Quest*, *68*(2), 193-206.

Horowitz-Kraus, T., DiFrancesco, M., Kay, B., Wang, Y., & Holland, S. K. (2015a). Increased resting-state functional connectivity of visual-and cognitive-control brain networks after training in children with reading difficulties. NeuroImage: Clinical, 8, 619-630.

Horowitz-Kraus, T., Toro-Serey, C., & DiFrancesco, M. (2015c). Increased resting-state functional connectivity in the cingulo-opercular cognitive-control network after intervention in children with reading difficulties. PloS one, 10(7), e0133762.

Hou, X., Zhang, Z., Zhao, C., Duan, L., Gong, Y., Li, Z., & Zhu, C. (2021). NIRS-KIT: a MATLAB toolbox for both resting-state and task fNIRS data analysis. *Neurophotonics*, *8*(1), 010802.

Jensen, J., Lindgren, M., Andersson, K., Ingvar, D. H., & Levander, S. (2000). Cognitive intervention in unemployed individuals with reading and writing disabilities. Applied neuropsychology, 7(4), 223-236.

Joo, S. J., Tavabi, K., Caffarra, S., & Yeatman, J. D. (2021). Automaticity in the reading circuitry. *Brain and Language*, *214*, 104906.

Kemp, N., Parrila, R. K., & Kirby, J. R. (2009). Phonological and orthographic spelling in high-functioning adult dyslexics. Dyslexia, 15(2), 105-128. https://doi.org/10.1002/dys.364

Koyama, M. S., Di Martino, A., Kelly, C., Jutagir, D. R., Sunshine, J., Schwartz, S. J., ... & Milham, M. P. (2013). Cortical signatures of dyslexia and remediation: an intrinsic functional connectivity approach. *PloS one*, *8*(2), e55454.

Koyama, M. S., Di Martino, A., Zuo, X. N., Kelly, C., Mennes, M., Jutagir, D. R., ... & Milham, M. P. (2011). Resting-state functional connectivity indexes reading competence in children and adults. *Journal of Neuroscience, 31*(23), 8617-8624.

Koyama, M. S., Kelly, C., Shehzad, Z., Penesetti, D., Castellanos, F. X., & Milham, M. P. (2010). Reading networks at rest. Cerebral cortex, 20(11), 2549-2559.

Kronbichler, L., & Kronbichler, M. (2018). The Importance of the Left Occipitotemporal Cortex in Developmental Dyslexia. Current Developmental Disorders Reports, 5(1), 1–8. https://doi.org/10.1007/s40474-018-0135-4

Law, J. M., Wouters, J., & Ghesquière, P. (2015). Morphological awareness and its role in compensation in adults with dyslexia. Dyslexia, 21(3), 254-272. https://doi.org/10.1002/dys.1495

Layes, S., Guendouz, M., Lalonde, R., & Rebai, M. (2022). Combined phonological awareness and print knowledge training improves reading accuracy and comprehension in children with reading disabilities. *International Journal of Disability, Development and Education*, *69*(4), 1185-1199.

Lefly, D. L., & Pennington, B. F. (1991). Spelling errors and reading fluency in compensated adult dyslexics. *Annals of dyslexia*, *41*, 141-162.

Liakakis, G., Nickel, J., & Seitz, R. (2011). Diversity of the inferior frontal gyrus—a meta-analysis of neuroimaging studies. *Behavioural brain research*, *225*(1), 341-347.

Livingston, E. M., Siegel, L. S., & Ribary, U. (2018). Developmental dyslexia: Emotional impact and consequences. Australian Journal of Learning Difficulties, 23(2), 107–135. https://doi.org/10.1080/19404158.2018.1479975

Lovett, M. W., Frijters, J. C., Steinbach, K. A., Sevcik, R. A., & Morris, R. D. (2021). Effective intervention for adolescents with reading disabilities: Combining reading and motivational remediation to improve outcomes. Journal of Educational Psychology, 113(4), 656.

Lyon, G. R., Shaywitz, S. E., & Shaywitz, B. A. (2003). A definition of dyslexia. Annals of Dyslexia, 53(1), 1–14. doi:10.1007/s11881-003-0001-9

Macdonald, S. J. (2009). Windows of reflection: conceptualizing dyslexia using the social model of disability. *Dyslexia*, *15*(4), 347-362.

Manis, F. R., Szeszulski, P. A., Holt, L. K., & Graves, K. (1990). Variation in component word recognition and spelling skills among dyslexic children and normal readers. In T. H. Carr & B. A. Levy (Eds.), Reading and its development: Component Skills Approaches. (pp. 207-259). Academic Press.

Maughan, B., Messer, J., Collishaw, S., Pickles, A., Snowling, M., Yule, W. & Rutter, M. (2009). Persistence of literacy problems: Spelling in adolescence and at mid-life. Journal of Child Psychology and Psychiatry, 50(8), 893-901. https://doi.org/10.1111/j.1469-7610.2009.02079.x

McCandliss, B. D., Cohen, L., & Dehaene, S. (2003). The visual word form area: expertise for reading in the fusiform gyrus. *Trends in cognitive sciences*, *7*(7), 293-299.

Molko, N., Cohen, L., Mangin, J. F., Chochon, F., Lehéricy, S., Le Bihan, D., & Dehaene, S. (2002). Visualizing the neural bases of a disconnection syndrome with diffusion tensor imaging. *Journal of Cognitive Neuroscience*, *14*(4), 629-636.

Norton, E. S., Beach, S. D., & Gabrieli, J. D. (2015). Neurobiology of dyslexia. *Current opinion in neurobiology*, *30*, 73-78.

Nukari, J. M., Laasonen, M. R., Arkkila, E. P., Haapanen, M. L., Lipsanen, J. O., & Poutiainen, E. T. (2022). Neuropsychological intervention of dyslexia has a positive effect on aspects of psychological well-being in young adults–a randomized controlled study. Dyslexia, 28(2), 166-184

Nukari, J. M., Poutiainen, E. T., Arkkila, E. P., Haapanen, M.-L., Lipsanen, J. O., & Laasonen, M. R. (2020). Both individual and group-based neuropsychological interventions of dyslexia improve processing speed in young adults: A randomized controlled study. Journal of Learning Disabilities, 53(3), 213–227. https://doi.org/10.1177/0022219419895261

Pennington, B. F., McCabe, L. L., Smith, S. D., Lefly, D. L., Bookman, M. O., Kimberling, W. J., & Lubs, H. A. (1986). Spelling errors in adults with a form of familial dyslexia. Child Development, 57(4), 1001-1013. https://doi.org/10.2307/1130374

Pinti, P., Scholkmann, F., Hamilton, A., Burgess, P., & Tachtsidis, I. (2019). Current status and issues regarding pre-processing of fNIRS neuroimaging data: an investigation of diverse signal filtering methods within a general linear model framework. *Frontiers in human neuroscience*, *12*, 505.

Richlan, F., Kronbichler, M., & Wimmer, H. (2009). Functional abnormalities in the dyslexic brain: A quantitative meta‐analysis of neuroimaging studies. Human brain mapping, 30(10), 3299-3308.

Richlan, F., Kronbichler, M., & Wimmer, H. (2013). Structural abnormalities in the dyslexic brain: A meta‐analysis of voxel‐based morphometry studies. *Human brain mapping*, *34*(11), 3055-3065.

Saito, Y., Garza, T. J., & Horwitz, E. K. (1999). Foreign language reading anxiety. The modern language journal, 83(2), 202-218.

Schurz, M., Wimmer, H., Richlan, F., Ludersdorfer, P., Klackl, J., & Kronbichler, M. (2015). Resting-state and task-based functional brain connectivity in developmental dyslexia. *Cerebral Cortex*, *25*(10), 3502-3514.

Schutte, N. S., & Malouff, J. M. (2007). Dimensions of reading motivation: Development of an adult reading motivation scale. Reading psychology, 28(5), 469-489.

Schlaggar, B. L., & Church, J. A. (2009). Functional neuroimaging insights into the development of skilled reading. Current Directions in Psychological Science, 18(1), 21-26.

Siegel, L. S., Share, D., & Geva, E. (1995). Evidence for superior orthographic skills in dyslexics. Psychological Science, 6(4), 250-254. https://doi.org/10.1111/j.1467-9280.1995.tb00601.x

Shaywitz, B. A., Shaywitz, S. E., Pugh, K. R., Mencl, W. E., Fulbright, R. K., Skudlarski, P., & Gore, J. C. (2002). Disruption of posterior brain systems for reading in children with developmental dyslexia. Biological psychiatry, 52(2), 101-110.

Tops, W., Callens, M., Bijn, E., & Brysbaert, M. (2014). Spelling in adolescents with dyslexia: Errors and modes of assessment. Journal of Learning Disabilities, 47(4), 295- 306. https://doi.org/10.1177/0022219412468159

Torgeson, J. K., Wagner, R. K., & Rashotte, C. A. (1999). Test of word reading efficiency. Austin, TX: Pro-Ed.

Van der Mark, S., Klaver, P., Bucher, K., Maurer, U., Schulz, E., Brem, S., ... & Brandeis, D. (2011). The left occipitotemporal system in reading: disruption of focal fMRI connectivity to left inferior frontal and inferior parietal language areas in children with dyslexia. *Neuroimage*, *54*(3), 2426-2436.

Wechsler, D. (1999). Wechsler abbreviated scale of intelligence

Welcome, S. E., Leonard, C. M., & Chiarello, C. (2010). Alternate reading strategies and variable asymmetry of the planum temporale in adult resilient readers. Brain and language, 113(2), 73-83.

Wilkinson, G., & Robertson, G. (2006). Wide Range Achievement Test 4 (WRAT-4). Psychological Assessment Resources.

Wilson, Alexander M., and Nonie K. Lesaux. 2001. Persistence of phonological processing deficits in college students with dyslexia who have age-appropriate reading skills. Journal of Learning Disabilities 34: 394–400.

Withers, A., 2012. Disability Politics and Theory. Fernwood Publishing.

Woodcock, R. N. (2011). Woodcock reading mastery tests (3rd edn.). Circle Pines, MN: American Guidance Service

Vender, M., Melloni, C., & Delfitto, D. (2022). The effectiveness of reading intervention in adults with developmental dyslexia: A systematic review. *Italian journal of linguistics*, *34*(1), 189-232.

Yang, L., Li, C., Li, X., Zhai, M., An, Q., Zhang, Y., Zhao, J., & Weng, X. (2022). Prevalence of Developmental Dyslexia in Primary School Children: A Systematic Review and MetaAnalysis. Brain Sciences, 12(2), 240. https://doi.org/10.3390/brainsci12020240

Yan, X., Jiang, K., Li, H., Wang, Z., Perkins, K., & Cao, F. (2021). Convergent and divergent brain structural and functional abnormalities associated with developmental dyslexia. *elife*, *10*, e69523.

Ye, Z., Rüsseler, J., Gerth, I., & Münte, T. F. (2017). Audiovisual speech integration in the superior temporal region is dysfunctional in dyslexia. *Neuroscience*, *356*, 1-10.

Zhang, X., Lecce, S., Ceccato, I., Cavallini, E., Zhang, L., & Chen, T. (2018). Plasticity in older adults' theory of mind performance: the impact of motivation. *Aging & Mental Health*, *22*(12), 1592-1599.

9. Appendices

Table 1: Channels with poor scalp coupling indexes
*Channels with poor scalp coupling indexes(values below 0.5) that were removed prior to data analysis. * indicates this participant was removed from data analysis entirely, for one or more regions of interest*

Participant	Channels with scalp coupling index < 0.5
P01- G	PRE: 6-4, 14-11, 8-5 POST: 4-3,7-5, 9-6, 10-8, 14-11, 19-4, 20-16,
P03 - S	PRE: 1-2, 2-1, 2-2, 2-3, 3-1, 5-4, 5-5, 6-4, 7-5, 7-7, 8-7, 9-7, 10-6, 15-2 POST: 1-2, 6-4
P07 - S	PRE: 4-3, 6-4, 13-9, 13-11, 14-10, 14-11, 20-16 POST: 2-1, 2-2, 4-2, 4-3, 5-4, 6-4, 12-11, 13-9, 13-11, 14-11, 20-16
P08- S	PRE: 1-2, 3-1, 4-2, 4-3, 6-4, 7-4, 11-10, 14-10, 14-11 POST: 1-2, 4-2, 4-3, 6-4, 11-10, 12-9, 12-10, 14-10, 14-11
P09- S	PRE: 4-3, 6-4, 13-9, 13-11 POST: 1-2, 2-3, 4-3, 6-4, 11-10, 12-9, 14-10, 15-12, 18-15
P10 - S	PRE: 2-1, 6-4 POST: 3-1, 3-3, 5-4, 15-12, 20-16
P11 - G	PRE: 3-1, 4-2, 4-3, 5-4, 13-9 POST: 3-1, 6-4, 8-5, 10-8, 13-9, 14-10,
P12 - G	PRE: 1-2, 2-2, 5-4, 6-4, 12-10, 14-11 POST: 1-2, 5-4, 5-5, 6-4, 7-4, 8-5, 10-8, 15-12
P14 - G	PRE: 1-2, 2-1, 2-2, 5-4, 5-5, 6-4, 7-4, 7-5, 7-6, 7-7, **8-5**, 8-7, **9-7,** POST: 1-2, 2-2, 4-2, 4-3, 5-4, 5-5, 6-4, 7-4, 7-5, 7-7, **8-5,** 8-7, 11-10, 14-11, 15-12, 17-15
P15 - S	PRE: 1-2, 2-2, 2-3 ,4-2, 7-4, 7-5, 7-6, 7-7, **8-5,** 9-6, 10-6, 11-10, 14-11, 16-12, 16-14, 17-15, 18-15, 19-14, **19-15**, 19-16, 20-16 POST: 1-2, ,4-2, 4-3, 7-6, 7-7, **8-5,** 8-7, 9-6, 9-7, 10-6, 10-8, 11-10, 12-10, 12-11, 14-10, 15-13, 16-12, 17-15, **18-13,** 19-14, **19-15**, 20-16

P16 - S	PRE: 2-1, 4-3, 6-4, 8-5, 8-7, 13-9, 14-11 POST: 1-2, 4-2, 4-3, 5-4, 6-4, 12-11, 14-11, 16-12
P17 - S	PRE: 1-2, 6-4, 8-7 POST: 1-2, 2-1, 2-2, 2-3, 4-2, 4-3, 5-4, 5-5, 6-4, 7-4, 8-5, 8-7, 12-10, 14-10, 15-12, 16-12, 17-12
P18 - S	PRE: 1-2, 3-1, 5-4, 5-5, 6-4, 7-4, **8-5,** 15-12, 15-13, 16-12, 16-14, 17-12, 17-13, 17-14, 17-15, **18-13**, 18-15, 19-15, 20-14, 20-16 POST: 1-2, 3-1, 5-4, 5-5, 6-4, 7-4, **8-5,** 15-12, 15-13, 16-12, 16-14, 17-12, 17-13, 17-14, 17-15, **18-13**, 18-15, **19-15**, 20-14, 20-16
P19 - G	PRE: 6-4, 20-16 POST: 1-2, 6-4, 10-8, 20-16
P21 - G	PRE: 6-4, 12-9, 12-11 POST: 5-4, 6-4
P30 - G	PRE: 15-12 POST: 12-11
P32 - G	PRE: 1-2, 2-2, 2-3, 4-2, 4-3, 6-4, 7-6, 8-5, 9-6, 10-6, 11-10, 12-9, 12-10, 14-10, 19-14, 20-16 POST: 2-2, 3-3, 9-6, 10-8, 13-9, 14-11, 19-14, 20-16
P33 - G	PRE: 1-2, 2-2, 2-3 ,4-2, 4-3, 5-4, 5-5, 6-4, 7-4, 7-5, 7-6, 7-7, **8-5,** 9-6, 10-6, 10-8, 11-10, 14-10, 14-11, 16-12, 16-14, 17-12, 17-14, 17-15, 18-15, 19-14, **19-15**, 19-16, 20-14, 20-16 POST: 1-2, ,4-2, 4-3, 5-4, 5-5, 6-4, 7-4, 7-5, 7-6, 7-7, **8-5,** 8-7, 9-6, 9-7, 10-6, 10-8, 11-10, 12-10, 12-11, 14-10, 14-11, 15-13, 16-12, 16-14, 17-12, 17-14, 17-15, **18-13,** 19-14, **19-15**, 20-14, 20-16
P34 - G	PRE: 1-2, 2-2, 3-1, 3-3, 4-2, 7-5, 7-6, 10-6, 12-9, 12-10 POST: 1-2, 2-2, 3-3, 6-4, 10-6, 11-10, 12-9, 15-13, 17-13, 20-14
P35 - S	PRE: 6-4, 9-6, 10-8, 12-9, 19-14, 20-16 POST: 2-1, 3-3, 6-4, 13-11, 20-16

Table 2: Neuroimaging Results LH

Raw p-value data assessing strength of functional connectivity before and after administering the training program. Compiled group data.

Channel	P-value	**Channel**	P-value
Left Superior Temporal Gyrus		Left Fusiform Gyrus	
10 - RH Inferior Parietal Region	0.0350*	15 - RH Parieto-Occipital Sulcus	0.0449*
		25 - LH Frontal Region	0.0311*
		32 - LH Inferior Parietal Region	0.0468*
		40 - LH Occipital Region	0.0307*
		41 - LH Posterior Temporal Region	0.0419*
		43 - LH Occipital Region	0.0428*

*P<0.05 **P<0.01

Table 3**:** Neuroimaging Results RH

Raw p-value data assessing strength of functional connectivity before and after administering the training program. Compiled group data.

Channel	P-value	**Channel**	P-value
Right Superior Temporal Gyrus		Right Fusiform Gyrus	
13 - RH Occipital Region	0.0464*	N/A	
22 - LH Frontal Region	0.00611**		

*P<0.05 **P<0.01

Table 4: Neuroimaging Results: Group Differences Skill

Raw p-value data assessing strength of functional connectivity before and after administering the training program.

Channel	P-value	**Channel**	P-value
Left Superior Temporal Gyrus		Left Fusiform Gyrus	
N/A		6 - RH Frontal Region	0.0356*
Right Superior Temporal Gyrus		Right Fusiform Gyrus	
N/A		N/A	

*P<0.05 **P<0.01

Table 5: Neuroimaging Results: Group Differences Goal

Raw p-value data assessing strength of functional connectivity before and after administering the training program.

Channel	P-value	**Channel**	P-value
Left Superior Temporal Gyrus		Left Fusiform Gyrus	
23 - LH Frontal Region	0.0258*	18 - RH Occipital Region	0.00148**
		38 - LH Occipital Region	0.0400*
Right Superior Temporal Gyrus		Right Fusiform Gyrus	
13 - RH Occipital Region	0.0432	N/A	

*P<0.05 **P<0.01

Table 6: Behavioural Results

Raw p-value and mean score data from the paired t-test assessing the change in behavioral scores before and after administering the training program.

	Skill			**Goal**		
	pre mean	*post mean*	*t-test*	*pre mean*	*post mean*	*t-test*
TOWRE Fluency - Real Word	1.34	1.57	0.0036**	1.56	1.73	0.0270*
TOWRE Fluency - Non Word	0.61	0.76	0.0019**	0.797	0.938	0.0058**
Word Identification - Woodcock	71.9	82.1	0.0046**	93.8	105.1	0.0091**
Word Attack - Woodcock	71.4	79.5	0.0415*	89.1	95.0	0.0130*
Passage Comprehension - Woodcock	80.5	90.7	0.0205*	92.3	104.5	0.0052**
Spelling Subtest - WRAT	57.0	59.3	0.0799*	66.1	70.8	0.0081**
Reading Self Efficacy	82.8	88.2	0.2328	70.9	75.1	0.1055
Reading Motivation	59.0	63.1	0.0150*	57	59.8	0.0352*
Reading Anxiety	38.9	38.7	0.3845	42.7	40.0	0.1151

*P<0.05 **P<0.01

Figure 1: Optode Placement

Exact placement of optode pairing that corresponds to the left (top) and right (bottom) hemispheres. The left superior temporal gyrus corresponds to the 19-15 optode pair (19/15), and the left fusiform gyrus corresponds to the 18-13 optode pair. The right superior temporal gyrus corresponds to the 9-7 optode pair (9/7), and the right fusiform gyrus corresponds to the 8-5 optode pair. This figure also labels channels 1 to 44.

T= transmitter R= receiver

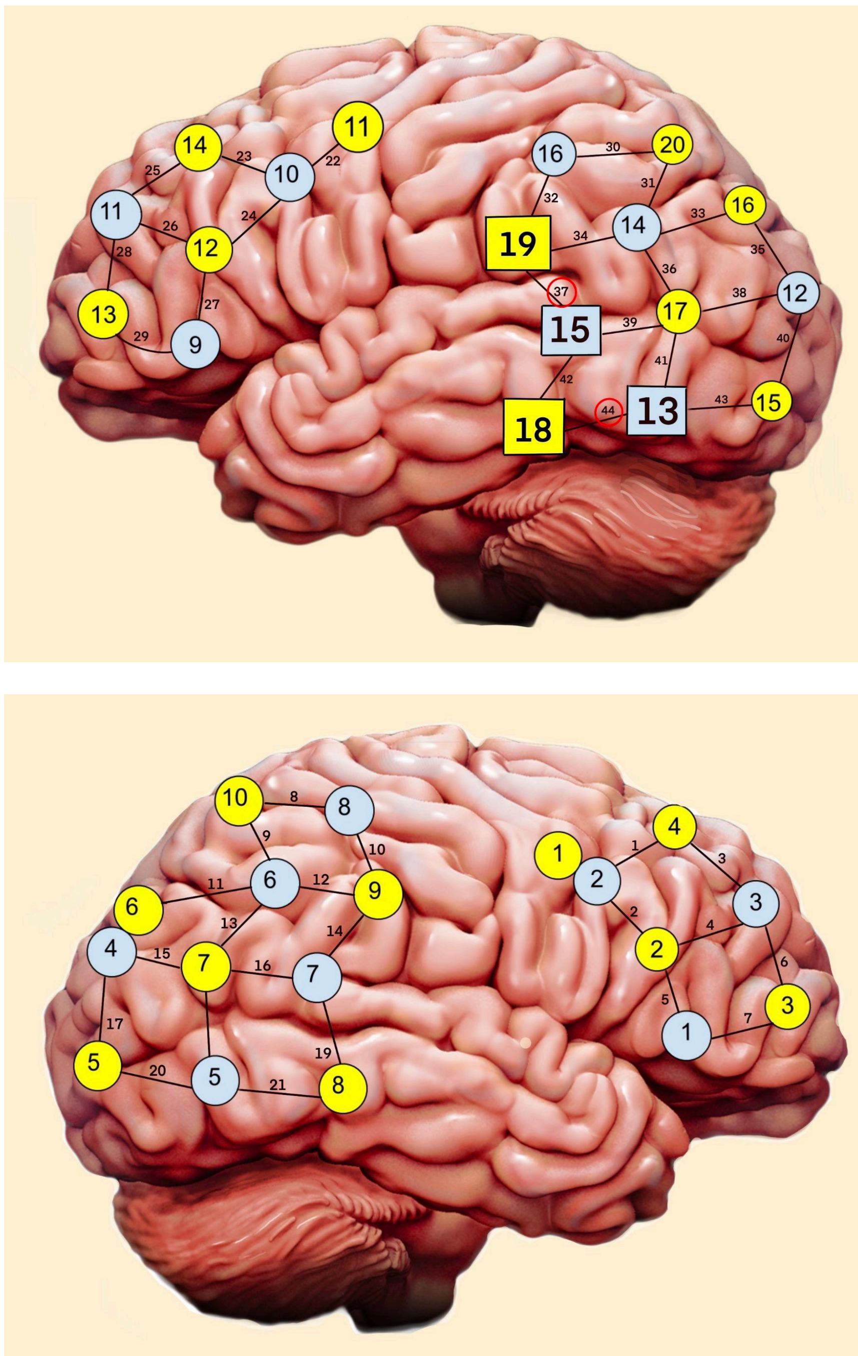


Figure 2: Analysis and Preprocessing Flowchart

Flowchart of preprocessing and analysis steps of resting state fNIRS data

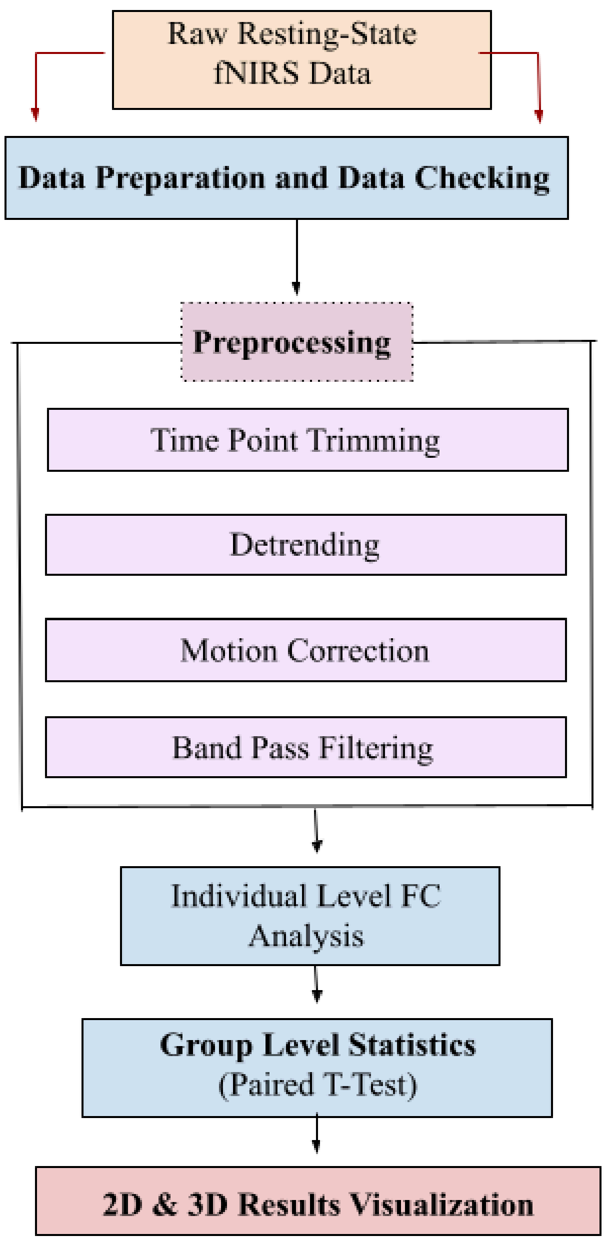


Figure 3: Probe and channel configuration

Probe and channel configuration for the right (top) and left (bottom) hemisphere fNIRS devices used in analysis of resting state data.

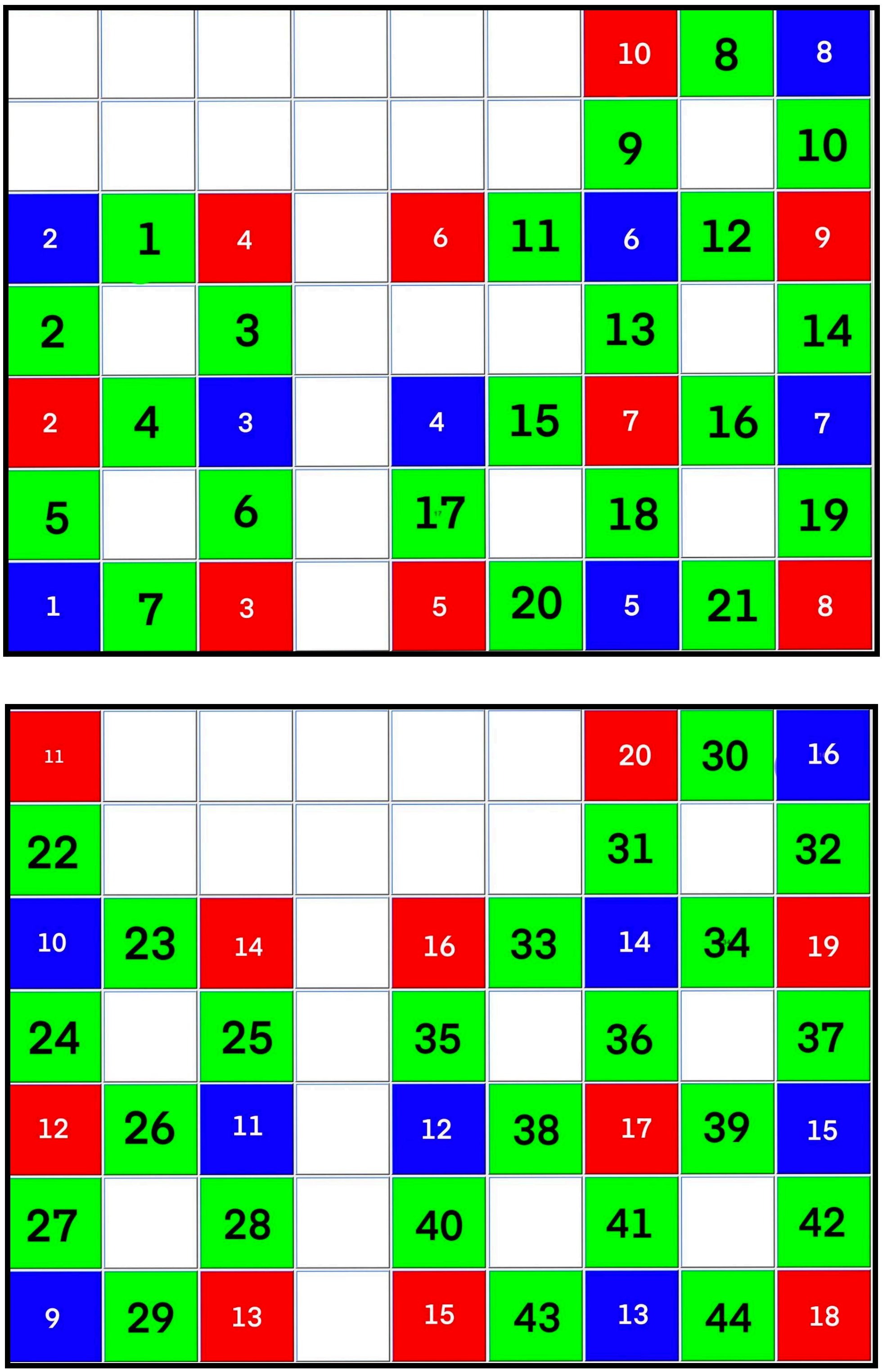


Figure 4: Behavioural Results Line Graphs

Line Graphs showing improvements in standardized behavioral literacy tasks, and psychosocial measures before and after training.

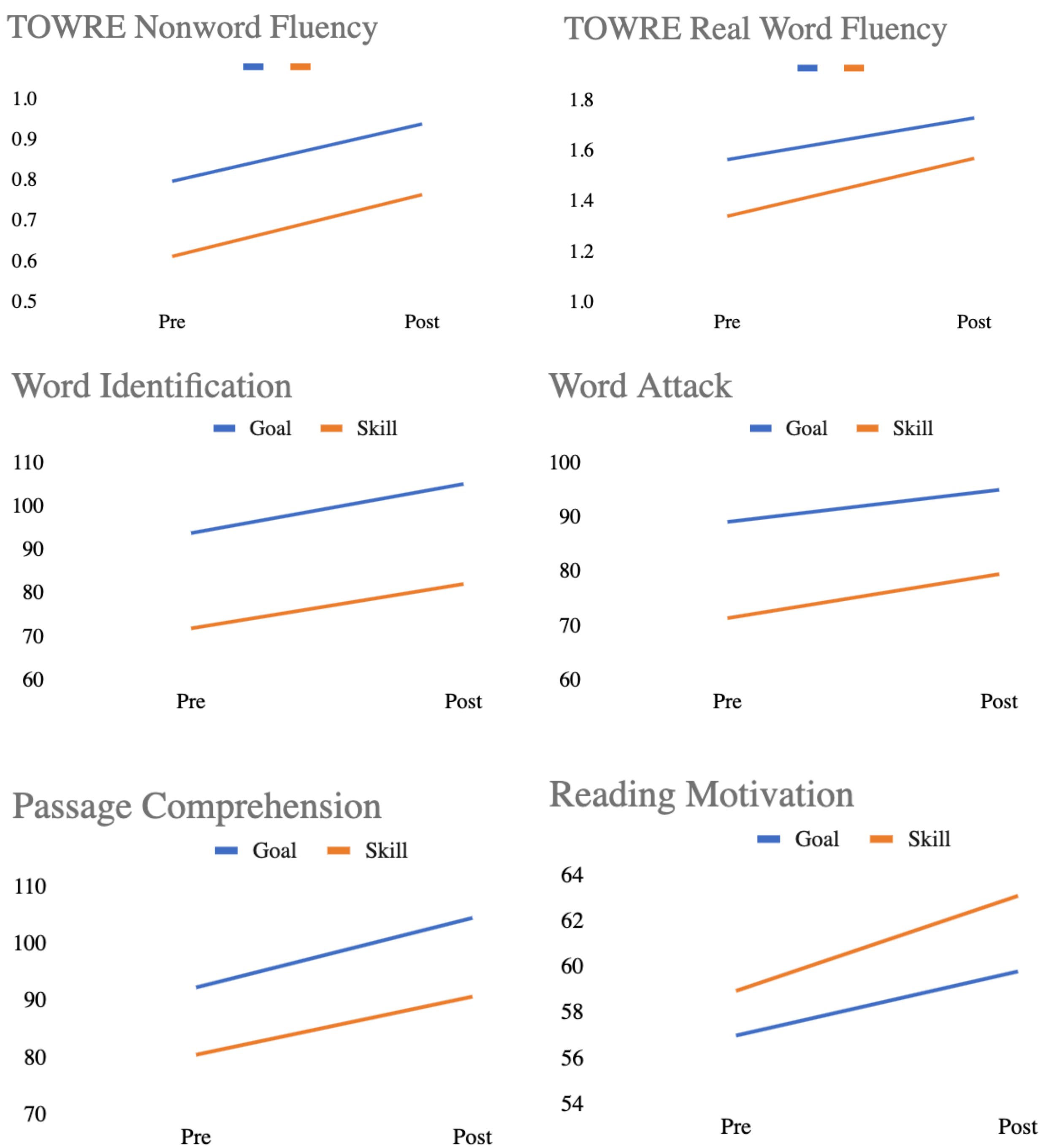
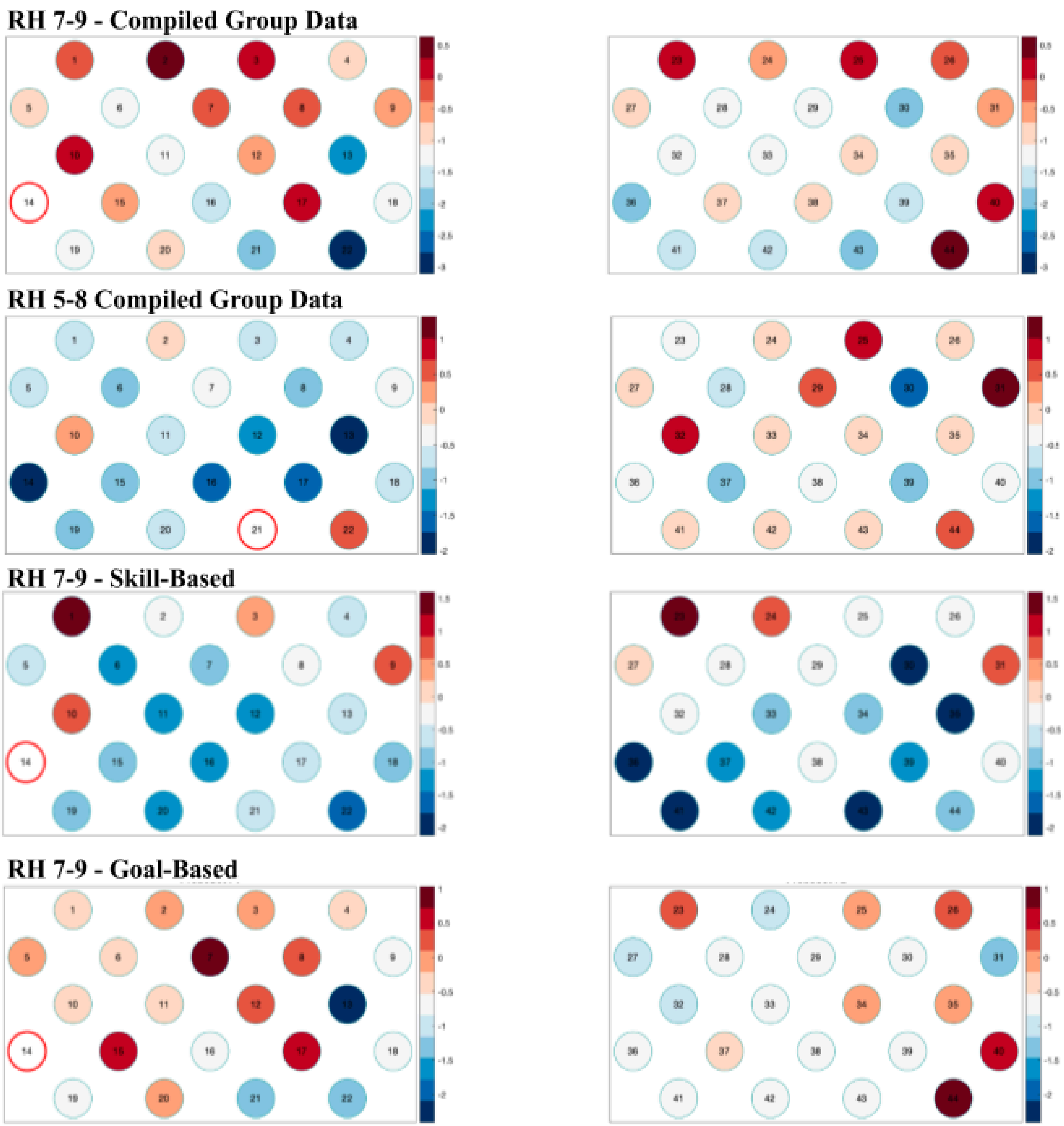
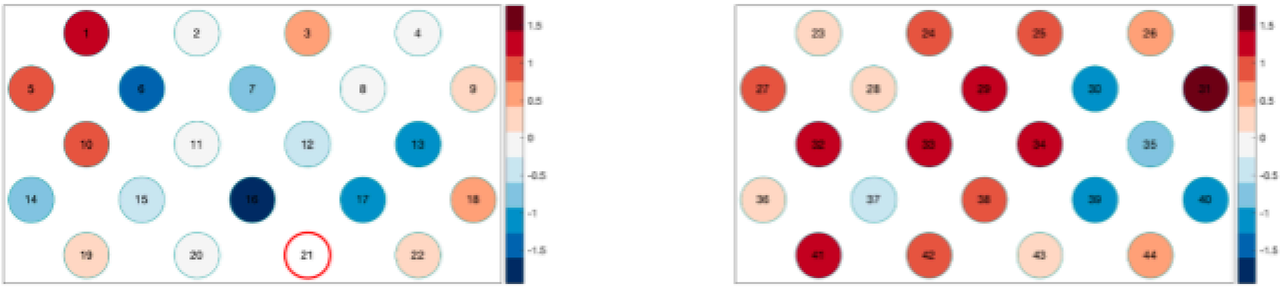


Figure 5: Neuroimaging Heat Map (LH)

Results map from the left hemisphere analysis. Deeper red signals channels with increased resting state functional connectivity as a result of training. Deeper blue signals decreased RSFC in channels.



RH 5-8 - Skill-Based



RH 5-8 - Goal-Based

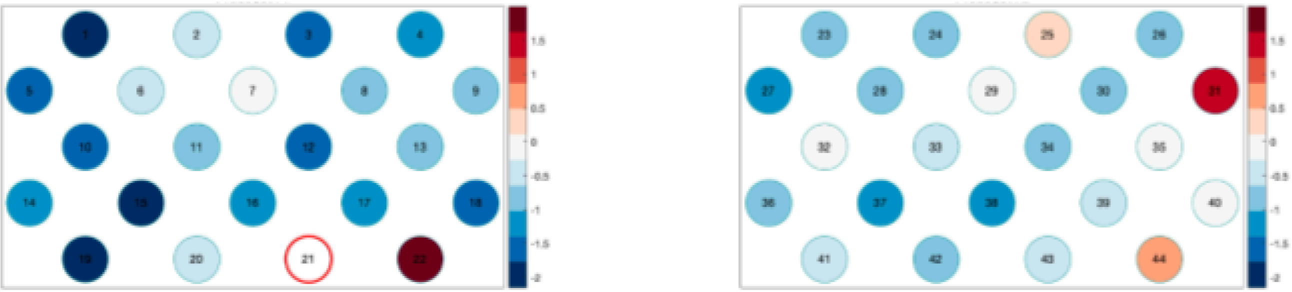
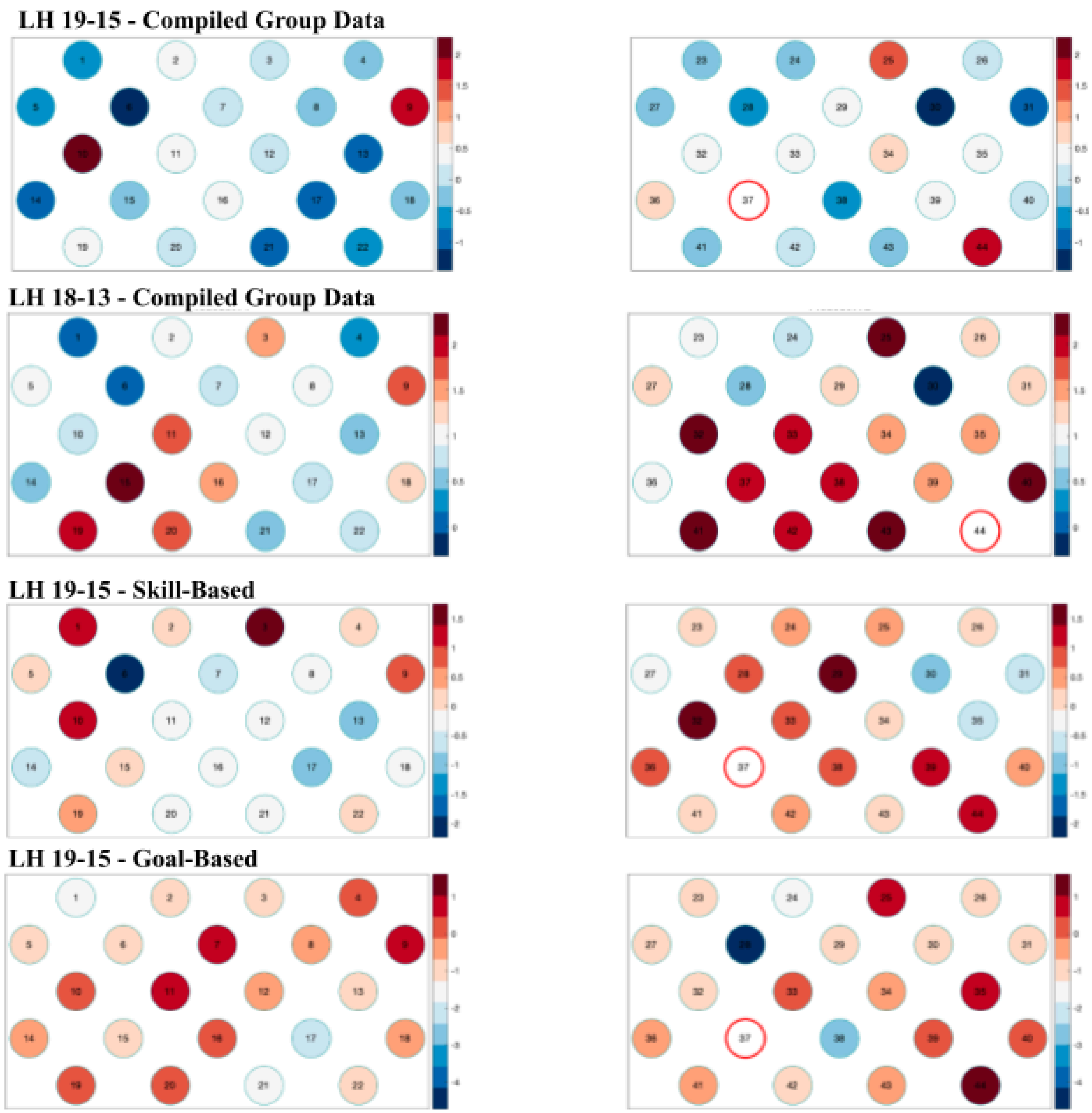
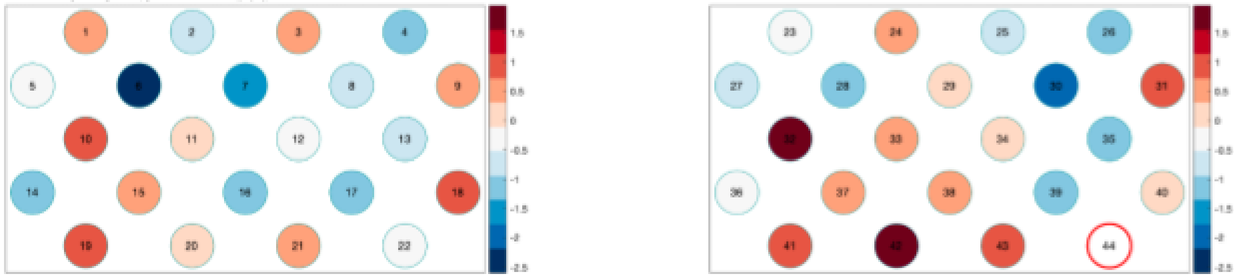


Figure 5: Neuroimaging Heat Map (RH)

Results map from the right hemisphere analysis. Deeper red signals channels with increased resting state functional connectivity as a result of training. Deeper blue signals decreased RSFC in channels.



LH 18-13 - Skill-Based



LH 18-13 - Goal-Based