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A Comprehensive Study of Neural Entrainment in Developmental Language Disorder and Reading Disability

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Abstract

Prior research has suggested that reading disability (RD, dyslexia) and developmental language disorder (DLD) stem from deficits in rhythmic auditory processing, specifically in synchronizing neural oscillations (Cumming et al., 2015; Goswami, 2011). Speech relies on rhythmic patterns for signaling linguistic information at multiple timescales (e.g., phonemes, syllables; Giraud & Poeppel, 2012). The disruption of regular neural entrainment is hypothesized to lead to difficulties in processing fast acoustic changes in speech, negatively affecting phonological processing, and speech segmentation. In this dissertation, I studied neural entrainment to uncover possible areas of impairment related to speech tracking, which could help inform interventions. In Chapter 2, I present a systematic review summarizing the state of research on neural entrainment in children and adults with DLD or RD. The strongest evidence of impairment was observed in RD, demonstrating atypical neural entrainment to prosody, syllables, and phonemes compared to typically developing (TD) individuals. In contrast, only two studies were conducted on children with DLD, demonstrating the need for more research in this area. Chapters 3 and 4 address some of the gaps highlighted in Chapter 2 by investigating neural entrainment in children with a broad range of language and reading abilities, including children with RD and DLD. I used electroencephalography (EEG) data from the Healthy Brain Network, which allowed me to investigate neural entrainment in many children. In Chapter 3, I measured cerebro-acoustic phase coherence and only found neural entrainment for a small band (3.25-5 Hz), demonstrating syllabic entrainment. However, there were no differences in syllabic entrainment based on language or reading abilities nor clinical diagnoses of RD and DLD. Since coherence was not powerful enough to detect neural entrainment outside of a small band, in Chapter 4, I used encoding models which have shown neural entrainment with shorter amounts of neuroimaging data (Mesik & Wojtczak, 2023). The findings demonstrate robust neural entrainment to acoustic and phonetic information as well as clear differences between RD and DLD compared to TD. Our results provide valuable insights into how neural entrainment to speech is modulated based on the presence of language or reading impairments.

Keywords

Dyslexia, reading disability, developmental language disorder, neural entrainment, language, coherence, systematic review, encoding model

Summary for Lay Audience

Research suggests that reading disability (RD, dyslexia) and developmental language disorder (DLD) come from problems in processing rapid auditory rhythms (Cumming et al., 2015; Goswami, 2011). Specifically, there may be issues with how our brainwaves are able to match with rhythms in speech. Speech relies on rhythmic patterns for signaling language information such as phonemes and syllables (Giraud & Poeppel, 2012). The process where our brainwaves match to rapid speech information is called neural entrainment. The disruption of neural entrainment is thought to lead to difficulties in processing fast changes in speech, negatively affecting phonological processing, and speech segmentation. In this dissertation, I studied neural entrainment to uncover possible areas of impairment related to speech tracking. In Chapter 2, I present a systematic review summarizing research on neural entrainment in children and adults with DLD or RD. The strongest evidence of impairment was observed in RD, demonstrating unusual neural entrainment to speech information compared to typically developing (TD) individuals. In contrast, only two studies were conducted on children with DLD, demonstrating the need for more research in this area. Chapters 3 and 4 address some of the gaps highlighted in Chapter 2 by investigating neural entrainment in children with a range of language and reading abilities, including children with RD and DLD. I used neural data from a large database, which allowed me to investigate neural entrainment in many children. In Chapter 3, I measured cerebro-acoustic phase coherence and found neural entrainment for a small band related to syllable entrainment. However, there were no differences in syllable entrainment based on language or reading abilities nor diagnoses of RD and DLD. Since coherence was not powerful enough to detect neural entrainment outside of a small band, in Chapter 4, I used encoding models which are good at measuring neural entrainment with shorter data (Mesik & Wojtczak, 2023). The findings demonstrate robust neural entrainment to acoustic and phonemic information as well as clear differences between RD and DLD compared to TD. Our results provide valuable insights into how neural entrainment to speech differs based on the presence of language or reading impairments.

Co-Authorship Statement

All projects were conceptualized, analyzed, and written by Christine Moreau and supervised by Dr. Marc Joanisse. Chapter 2 was a collaborative project with Dr. Leah Brainin, where she was second reviewer. She helped with title and abstract screening as well as full-text screening, and provided feedback on the manuscript. Dr. Christina Vanden Bosch der Nederlanden provided Matlab scripts and helped troubleshoot coding for data analysis of Chapter 3. She also provided feedback on the manuscript.

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List of Abbreviations

ADHD	Attention Deficit Hyperactivity Disorder
AM	Amplitude Modulated
ASSR	Auditory Steady-State Response
AST	Asymmetric Sampling in Time
BOLD	Blood Oxygen Level Dependent
CAPC	Cerebro-acoustic phase coherence
CELF	Comprehensive Evaluation of Language Fundamentals
CTOPP	Comprehensive Test of Phonological Processing
CTS	Cortical Tracking of Speech
DLD	Developmental Language Disorder
ECoG	Electrocorticography
EEG	Electroencephalography
EOG	Electrooculogram
EVT	Expressive Vocabulary Test
F	Phonetic features
FDR	False Discovery Rate
fMRI	functional Magnetic Resonance Imaging
FS	Phonetic and spectrogram features
FSIQ	Full-Scale Intelligence Quotient
HBN	Healthy Brain Network
IFG	Inferior Frontal Gyrus
IHPS	Inter-Hemispheric Phase Synchronization
IPA	International Phonetic Alphabet
ITC	Inter-Trial Phase Coherence
IQ	Intelligence Quotient
LCODC	Listening Comprehension and Oral Discourse
LH	Left Hemisphere
M	Mean
MANOVA	Multivariate Analysis of Variance
M/F	Male/female
MEG	Magnetoencephalography
mTRF	multivariate Temporal Response Function
PCA	Principal Components Analysis
PLI	Phase Lag Index
PLV	Phase Locking Value
PPVT	Peabody Picture Vocabulary Test
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
RAN	Rapid Automatized Naming
RAP	Rapid Auditory Processing
RD	Reading Disability
RDNoPho	RD with no phonological deficits
RDPho	RD with phonological deficits
RH	Right Hemisphere
rmax	Maximum Correlation
ROI	Region of Interest
RSN	Rapid Symbol Naming

S	Spectrogram
SD	Standard deviation
SID	Study identification
SNR	Signal-to-Noise Ratio
tACS	Transcranial alternating current stimulation
TD	Typically Developing
TOWRE	Test of Word Reading Efficiency
TRF	Temporal Response Function
TSF	Temporal Sampling Framework
WIAT	Weschler Individual Achievement Test
WISC	Weschler Intelligence Scale for Children

Chapter 1

1 General Introduction

1.1 Language and Reading Disorders

For many, language learning is implicit, done without conscious effort. As infants, we learn to segment words by listening to the acoustic properties of speech (Saffran et al., 2006). By listening to fluent speech, infants implicitly learn the phonemes, stress patterns, and word boundaries of their native language (Jusczyk et al., 1999; Saffran et al., 2006). Learning the rhythm of language has been shown to occur as early as in utero (DeCasper & Spence, 1986; May et al., 2011; Ramus, 2002), demonstrating that the rhythmic information in speech is crucial for language learning. Linguistic stress is particularly important as infants use this cue to segment speech into meaningful units (e.g., Weber et al., 2004). Over the course of development, infants learn the difference between native and non-native phonemes (Werker & Tees, 1984), which is related to building their lexicon (Kuhl et al., 2008). Phonological processing, the use of the distinct units of sound –the phonemes – from language, is important for processing spoken and written language (Wagner & Torgesen, 1987). However, there are some instances when children struggle with phonological processing. Children with Developmental Language Disorder (DLD) and Reading Disability (RD) have difficulties in phonological processing (Bishop & Snowling, 2004; Catts et al., 2005). DLD is characterized by oral language difficulties, which include oral production and comprehension (Bishop et al., 2017), while RD is characterized by difficulties in reading fluency and decoding print (Hulme & Snowling, 2016). RD and DLD are estimated to be equally prevalent (~7% of the population each; Bishop, 2010; Peterson & Pennington, 2012) and can often co-occur

(~50%; Adlof & Hogan, 2018; Bishop & Snowling, 2004). Further, there is often an overlap in symptomatology wherein children with RD demonstrate similar language difficulties as children with DLD (Robertson et al., 2013) and children with DLD demonstrate similar difficulties in reading as children with RD (Tomblin et al., 2000). It is thought that poor reading abilities in children with RD are related to poor language skills and the inverse is true in DLD where poor language skills can lead to literacy problems (see Bishop & Snowling, 2004 for a review).

These disorders have many similarities, but they are not the same. Individuals with RD can have difficulties recognizing printed words, have poor reading fluency, comprehension, and spelling that is not attributed to sensory or neurocognitive deficits (e.g., vision loss, autism spectrum disorder; Bishop & Snowling, 2016; Lyon et al., 2003). DLD is likewise precluded in individuals with biomedical conditions. DLD encompasses a wide range of problems, including difficulties with grammar, semantics, pragmatics (understanding or producing language in a certain context), discourse (disconnected utterances), and verbal short-term memory (Bishop et al., 2017). Further, children with DLD are more prone to difficulties with attention and motor development (Gooch et al., 2013). RD and DLD have social, emotional, and educational impacts (Bishop et al., 2017; Cross et al., 2019; Duff et al., 2022; Livingston et al., 2018), which is why it is important to understand the underlying mechanisms behind both RD and DLD. More targeted interventions based on research findings could be developed to boost language and reading abilities. Further, although RD has received much attention in the research community, DLD is understudied (McGregor, 2020), and may go undiagnosed or misdiagnosed due to a lack of understanding and research in DLD. Thus, it is important to understand where these two disorders may differ when it comes to speech tracking.

1.2 Rhythmic Tracking Theories

The exact causes of RD and DLD are not fully understood and are likely due to a variety of factors, including genetics and neurobiological factors (Bishop et al., 2017; Hulme & Snowling, 2016). One of the most widely accepted theories of the origin of RD and DLD is that they stem from a difficulty with phonological processing (Goswami, 2011; Poeppel et al., 2008; Ramus et al., 2013). Phonological processing is crucial for various language-related tasks, encompassing the abilities to compare, segment, and discriminate phonemes (see Bishop & Snowling, 2004 for a more detailed overview). These skills are fundamental for understanding the sound structure of words. Moreover, the ability to apply letter-sound knowledge is important for the fluent recognition of written words and their correct pronunciation. Difficulties in phonological processing can lead to subsequent problems in reading and spoken language. This difficulty with phonological processing has been proposed to be a result of poor rhythmic tracking (Goswami, 2011). The ability to track rapid changes in speech is crucial for speech perception and phonological processing. A Rapid Auditory Processing (RAP) deficit was first proposed in DLD (Tallal, 1976; Tallal & Piercy, 1974), where children with DLD demonstrate difficulties discriminating rapid auditory information in the 20-50 ms range. This range is thought to correspond to processing phonetic information. Studies have found that relative to TD children, children with RD and DLD are poorer at ordering rapidly presented pairs of high- and low-frequency tones (e.g., Heath et al., 1999; Tallal, 1976), have poorer pitch discrimination between two rapidly presented tones (Tallal, 1980; Tallal & Piercy, 1973), and have slower reaction times compared to TD individuals (Neville et al., 1993; Nicolson & Fawcett, 1994). However, the findings related to this theory have been mixed (see Hämäläinen et al., 2012 and McArthur & Bishop, 2001 for reviews). The results primarily demonstrate RAP deficits in DLD rather than RD (Choudray et al., 2011) and several studies have failed to replicate the RAP findings (e.g., Bishop et al., 1999b; McAnally & Stein, 1996; Schulte-Korne et al., 1998). Importantly, multiple studies have demonstrated that children with RD and DLD have difficulties with all presentation rates and not just rapid rates (e.g., Bishop et al., 1999a; Marshall et al., 2001). More recent theories have emerged providing more specific explanations for auditory processing.

These theories emphasize the importance of the multiple timescales in speech processing (e.g., Ghitza, 2011; Goswami, 2011; Poeppel et al., 2008). The multi-time resolution models propose that the brain is simultaneously analyzing speech at multiple time scales synchronized to the input. This includes the shorter window (20-50 ms) corresponding to phonemic processing as well as the longer window (150–300 ms) corresponding to phrasal and syllabic information processing (Poeppel et al., 2008). Goswami's (2011) Temporal Sampling Framework (TSF) combines aspects of the multi-time resolution models and proposes that deficits at these timescales affect children's phonological development and therefore, various aspects of speech processing. Speech processing of these timescales is also thought to occur in a hierarchical manner, such that deficits in tracking larger units like syllables have a cascading effect on smaller units like phonemes (Leong & Goswami, 2015). This framework primarily focuses on the slower timescale which is related to syllable parsing and stress. The theory proposes that RD and

DLD have impaired rise time discrimination, which is crucial for speech perception. Rise times are important because they reset brain oscillations so that their peaks and troughs align with the peaks and troughs of amplitude modulations from the speech signal (Goswami, 2015). Rise time discrimination, conceptualized through the accuracy of tapping to the beat of the input, demonstrates reduced sensitivity to stress patterns and is a predictor of phonological awareness (Goswami et al., 2002, 2011; Thomson & Goswami, 2010). Behavioural results have demonstrated that individuals with RD and DLD have impaired rise time discrimination, which is related to phonological skills (Fraser et al., 2010; Goswami et al., 2011; Richards & Goswami, 2015).

1.3 Neural Entrainment

More recently, studies have analyzed sensitivity to rhythmic information in individuals with RD and DLD using neuroimaging methods, most commonly electroencephalography (EEG) and magnetoencephalography (MEG). These methods provide useful insight into the underlying processes involved in speech tracking because of its millisecond level precision. These neuroimaging methods investigate how strongly neural activity temporally synchronizes (‘entrains’) to speech and non-speech rhythms. This approach is called neural entrainment, which can be used to uncover neural oscillatory patterns related to visual, auditory, attentional, and memory processes (e.g., Calderone et al., 2014; Hickey & Race, 2021; Power et al., 2012). Neural entrainment is especially useful over non-imaging methods because it captures automatic, unconscious processes during speech processing. This can reveal subtle differences in speech processing between different populations that may not be apparent when relying solely on behavioural measures.

For this dissertation, we use neural entrainment in the broad sense (see Obleser & Kayser, 2019), wherein we investigate how neural activity synchronizes to speech or speech-like stimuli that is not necessarily oscillatory. The amplitude envelope of the stimuli can be broken down into several frequency bands related to different speech features (see Table 1.1). Syllable stress has been shown to occur at ~2 Hz (the delta band), syllable processing at ~5 Hz (the theta band), and phoneme processing at ~ 35 Hz (Ghitza et al., 2013; Goswami, 2011; Poeppel, 2014). Goswami (2019) recently added that onset-rime processing may occur ~ 20 Hz (beta; Leong & Goswami, 2015). Beta and gamma have also been linked to processing phonetic information and gamma to acoustic information (Ghitza, 2011; Giraud & Poeppel, 2012; Gross et al., 2013; Meyer, 2018). Inefficient neural entrainment to these frequency ranges may lead to difficulties in speech processing. Importantly, encoding at theta is hypothesized to be crucial for speech intelligibility whereas encoding at delta is hypothesized to be crucial for non-speech-specific acoustic rhythm processing (Ding & Simon, 2014; Doelling et al., 2014). Poor neural entrainment across varying frequency bands, or a combination thereof, may contribute to distinct difficulties, potentially resulting in varied disorders or manifestations of disorders.

While the multi-time resolution models do not extensively address the role of the alpha band (8-12 Hz), two compelling hypotheses emerge. One hypothesis is that alpha entrainment is related to phoneme tracking since a peak in the amplitude envelope has been found at the frequency related to phoneme presentation (Keitel et al., 2018; Vanden Bosch der Nederlanden). The other hypothesis is that the alpha band is related to the storage of verbal information in working memory (Meyer, 2018). It is thought to be related to sensory gating wherein brain regions that are not relevant to the task get disengaged so that irrelevant processes do not interfere with working memory (Haegans et al., 2010; Klimesch et al., 2007; Van Dijk et al., 2010). Studying neural entrainment at alpha is crucial for unraveling its role in language processing, advancing knowledge of the underlying cognitive processes.

Table 1.1. Frequency bands and their hypothesized function in speech processing.

Frequency Band	Hypothesized Function
Delta (< 4 Hz)	Processing prosodic information, such as intonation, stress, rhythm (Meyer, 2018)
Theta (4-7 Hz)	Syllable rates, onsets (Giraud & Poeppel, 2012)
Alpha (8-12 Hz)	Phoneme rates and/or verbal working memory (Keitel et al., 2018; Meyer, 2018)
Beta (13-30 Hz)	Processing phonemic information and onset-rimes (Giraud & Poeppel, 2012; Goswami, 2019)
Gamma (30-80 Hz)	Processing phonemic and acoustic information (Gross et al., 2013; Meyer, 2018)

The TSF hypothesizes that poorer neural entrainment in the lower frequency bands (under 10 Hz) is primarily related to speech tracking impairments in RD and DLD (Goswami, 2011). Indeed, neural entrainment in the lower frequency bands has been found to be impaired in RD (Mandke et al., 2022; Molinaro et al., 2016; Power et al., 2013). However, the TSF does not fully touch upon neural entrainment in the higher frequency bands, which have also been found to be weaker in RD (Lehongre et al., 2011; Lizarazu et al., 2015). This is where the RAP theory may explain findings in faster time windows, which more generally posits that weaker neural entrainment is due to a difficulty in tracking rapidly presented auditory information (Tallal & Pearcy, 1974).

Furthermore, Poeppel et al.'s (2008) multi-time resolution model also predicts atypical neural entrainment and lateralization at gamma in RD. Laterality has also been shown to have a role in successful (and impaired) speech tracking. The Asymmetric Sampling in Time (AST) theory posits that hemispheric laterality is crucial for successful speech processing (Poeppel, 2003, 2008). The idea is that there should be greater right hemisphere activity for slower rates and greater left hemisphere activity for faster rates (Giraud & Poeppel, 2012; Goswami, 2011; Poeppel, 2003, 2008). Children with impaired speech tracking abilities, such as those with RD and DLD, would demonstrate atypical or even reversed hemispheric activity compared to their TD peers.

Not as much is known about neural entrainment in DLD. Two studies found that children with DLD have weaker neural entrainment than TD children to rapid information presented in the beta-gamma bands (Heim et al., 2011, 2013). Other neuroimaging evidence indicates that individuals with DLD track rhythmic information differently in comparison to TD individuals. Gaudet et al. (2020) conducted a meta-analysis in which they looked at functional brain connectivity at rest and during language-related tasks in children with or at risk of language disorders (e.g., children born prematurely, children with dyslexia, language learning disorders, stuttering, and with autism spectrum disorder). They found that children with language learning disorder or stuttering had less left hemispheric specialization than TD children. In addition, studies using functional Magnetic Resonance Imaging (fMRI) have also found reduced left hemisphere lateralization compared to the right in DLD during language related tasks (see Evans & Brown, 2016 for a review). Studies using event-related potentials (ERPs) have also found that individuals with DLD have atypical timing and peak amplitudes for early occurring components (related to auditory processing; Bishop et al., 2012) and abnormal amplitude modulation and lateralization for the later components (related to lexical-semantic knowledge, syntactic knowledge, and working memory; Epstein et al., 2013; Evans et al., 2011; Weber-Fox et al., 2010). However, these findings are inconsistent which is attributed to the unreliable nature of identifying peaks within ERP components (Evans & Brown, 2016; Luck & Kappenman, 2012). The analyses used for measuring neural entrainment offer several advantages over ERP analyses. For instance, the EEG can be broken down into frequency, amplitude, and phase, providing different characterizations of the oscillatory brain activity (Morales & Bowers, 2022). Time-frequency analyses also provide a more comprehensive understanding of changes in neural activity across frequencies and time, which is especially useful for understanding speech tracking dynamics.

Neural entrainment can be measured using a variety of approaches. Commonly used neural entrainment approaches include coherence, cross-correlation, and the auditory steady-state response between two signals. Coherence quantifies the consistency of the phase and amplitude of the EEG signal with the auditory input over time (Bowyer, 2016). Cross-correlation also measures the similarity between two signals (-1 indicating a perfect negative correlation and 1 indicating a perfect positive correlation) at different time lags (a lag of zero means that the signals are perfectly synchronized in time; Abrams et al., 2009). The auditory steady-state response (ASSR) measures the synchronization of neural activity to the amplitude modulated frequency of the auditory stimulus (Picton et al., 2003). In addition to these measures, graph theory can be used to analyze the connectivity to the stimulus between brain regions (Stam & Van Straaten, 2012). This is useful as this can tell us not only whether neural entrainment is occurring but how the brain network is organized. These, and other measures of neural entrainment, can be used to assess whether differences in speech tracking are related to language and reading impairments.

1.4 Objectives and Overview

The primary objective of this dissertation is to gain a better understanding of RD and DLD by looking at how neural entrainment to speech is related to language and reading abilities. Since RD and DLD have common difficulties in phonological processing, it is thought that this stems from a common underlying deficit in neural entrainment. The following chapters delve into this possibility. In this dissertation, I present three connected studies in which I investigate neural entrainment in RD and DLD. In Chapter 2, I conduct a systematic review in order to gain a better understanding of the existing literature. I summarize the findings for each frequency band (i.e., delta, theta, alpha, beta, gamma), comparing children with RD or DLD to TD children. This allows for a more comprehensive understanding of the existing work on neural entrainment in RD and DLD, especially in relation to the existing theories. I also compiled the correlational findings since each frequency band has been hypothesized to be related to different speech features. This review highlights the gaps in the literature that still need to be addressed, including the much smaller number of studies in DLD compared to RD. The review also highlights the inconsistent methodologies and findings between studies, calling for the need for more standardized approaches to measuring neural entrainment.

Chapters 3 and 4 address some of the gaps discussed in Chapter 2. In Chapter 3, I investigate neural entrainment using a measure of coherence in children with a spectrum of language and reading abilities. This is done to determine whether children's neural entrainment differs based on their language and reading scores since certain measures have been demonstrated to be good predictors of RD (e.g., letter knowledge, phoneme awareness, rapid automatized naming; Caravolas et al., 2012; Hulme & Snowling, 2016) and DLD (e.g., expressive and receptive language; Bishop et al., 2017). As I demonstrate, only a small band at theta is significantly above chance and no differences in neural entrainment are found across children based on their language and reading scores nor their diagnoses. This might be a limitation of the method when using a relatively small sample of auditory and EEG data per individual. In Chapter 4, I assess phase locking using forward encoding models, which has been shown to be sensitive with short stimulus presentations (Di Liberto & Lalor, 2017; Mesik & Wojtczak, 2023). The findings demonstrate that differences in neural entrainment based on children's diagnoses of RD and DLD can be detected with as little as 5 minutes of data. Importantly, this is one of the first studies to directly compare neural entrainment between children with RD and DLD. Even though these two disorders have similar phonological processing difficulties, there are important differences in their neural entrainment patterns. I discuss the implications of these findings as well as future directions.

Chapter 5 summarizes the findings of Chapters 2, 3, and 4 and relates them back to the theories discussed here, in Chapter 1. I discuss the methodological implications as well as directions for future research. Overall, this dissertation provides novel information on neural entrainment in DLD as well as how neural entrainment in DLD may differ from RD. I discuss how these findings can be used to inform interventions based on improving speech tracking abilities. This research contributes to the large body of literature on how individuals with language-related disorders track speech, allowing for a better understanding of the neural patterns underlying speech processing. These findings provide an excellent foundation for future work, which should continue to look at neural entrainment to speech in diverse populations.

1.5 References

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Chapter 2

2 A Systematic Review of Neural Entrainment in Language and Reading Disorders

2.1 Introduction

2.1.1 Background

It is estimated that reading disability (RD, also referred to as developmental dyslexia) and developmental language disorder (DLD) each affect approximately 7% of the population (Bishop, 2010; Peterson & Pennington, 2012), and yet we still do not fully understand these disorders. RD is primarily described as the presence of severe difficulties in decoding print and poor reading fluency (Hulme & Snowling, 2016). DLD is described as a developmental delay in oral language abilities and is not caused by other conditions such as brain injury or autism spectrum disorder (DLD is a somewhat more inclusive name for what was previously labelled Specific Language Impairment; Bishop et al., 2017). Although the two represent separate diagnostic categories, they often co-occur (Bishop & Snowling, 2004). Children with RD have been found to have similar language difficulties as children with DLD (Robertson et al., 2013) and approximately half of the children with DLD have reading difficulties (Tomblin et al., 2000). Importantly, RD and DLD are both proposed to have difficulties in phonological processing (Catts et al., 2005). One proposal suggests that this difficulty with phonological processing is related to impairments in processing the rhythmic patterns of speech (Goswami, 2011; Richards & Goswami, 2015). Rhythmic entrainment (commonly measured through finger tapping) has been found to be impaired in children and adults with RD (Thomson & Goswami, 2008; Thomson et al., 2006), and could in part explain the perceptual and phonological difficulties with syllables, rhymes, and phonemes (Goswami, 2011). Behavioural findings in temporal auditory sampling in individuals with DLD mirror those found in individuals with RD (e.g., Cumming et al., 2015; Richards & Goswami, 2015). Neuroimaging methods have recently also been used to investigate the underlying brain processes that may be involved in tracking rhythmic patterns in speech. Electroencephalography (EEG) and magnetoencephalography (MEG) are especially useful in this regard as they can measure neuronal activity at the millisecond level. Using these methods, we can measure the synchronization of neuronal oscillations to rhythmic patterns, called neural entrainment (e.g., Haarmann et al., 2002; Luo & Poeppel, 2007). This approach lends itself especially well to the auditory domain given that speech relies critically on rhythmic patterns for signaling linguistic information at multiple levels (e.g., phonemes, syllables, metrical stress, phrasal boundaries; Giraud & Poeppel, 2012); moreover, contemporary models of reading ability and disability focus on the critical role that phonological processing plays in this regard (Ramus et al., 2003; Seidenberg, 2017). Studying neural entrainment can point to possible neural impairments related to speech tracking, which could help inform rhythm-based interventions for those with RD and DLD.

EEG oscillations at different frequencies are proposed to reflect separate aspects of perception and language. Neural entrainment at the delta (< 4 Hz), theta (4-7 Hz), alpha (8-12 Hz), beta (13-30 Hz), and gamma (>30 Hz) frequency bands have been proposed to be relevant to language processing and comprehension (Meyer, 2018; Poeppel, 2014). Delta has been associated with processing prosodic information such as stress patterns, metrical rhythm, and intonation (Meyer, 2018; Poeppel, 2003). Theta has been associated with syllable-level processing and is thought to be central for speech intelligibility (Ding & Simon, 2014; Giraud & Poeppel, 2012; Pellegrino et al., 2011; Poeppel, 2003). Further, delta and theta have been hypothesized to work together to group syllables into intonation phrases (Giraud & Poeppel, 2012; Meyer, 2018). Beta has been linked to top-down lexical-semantic predictions, as well as processing phonemic information (Ghitza, 2011; Meyer, 2018). The gamma band has also been related to processing phonemic as well as acoustic information (Giraud & Poeppel, 2012; Gross et al., 2013; Meyer, 2018). Further, theta and gamma have been hypothesized to work together to bind phonemic representations within syllabic representations. Conversely, research linking alpha band to language processing is not as prevalent but has been related to the storage of syntactic phrases in verbal working memory (Meyer, 2018), and phoneme processing (Keitel et al., 2018; Vanden Bosch der Nederlanden et al., 2020).

Our aim in the present work is to review research linking oscillatory indices of language processing to reading or language disabilities. Multiple theories have emerged linking temporal auditory deficit to RD and/or DLD (Goswami, 2011; McArthur & Bishop, 2004; Tallal & Piercy, 1973). For instance, the Rapid Auditory Processing (RAP) theory hypothesizes that children with DLD have difficulties processing rapidly changing acoustic information (20-50 ms) which would make it difficult to determine word boundaries (Tallal & Piercy, 1973). This has also been found to pattern with speech perception and phonological awareness difficulties in children with RD (Boets et al., 2011). The Temporal Sampling Framework (TSF), a more recent and complementary theory, focuses on slower rates (< 10 Hz) and posits that difficulties entraining to rhythmic information in this range could explain difficulties with syllable parsing, perceiving syllable stress and phonological awareness (Goswami, 2011; Poeppel, 2003). Further, the Asymmetric Sampling in Time (AST) theory posits that hemisphere laterality has crucial implications for successful language processing (Poeppel, 2003). Typical language processing has been associated with right hemisphere lateralization for slower rates (i.e., delta, theta) and left hemisphere lateralization for the faster rates (i.e., beta, gamma; Abrams et al., 2008; Boemio et al., 2005; Giraud & Poeppel, 2012). Difficulties in language and reading may be related to poor encoding and processing of temporal speech information, related to atypical alignment of neuronal oscillations, and thus marked by atypical patterns of lateralization indicative of abnormal neural entrainment among speech-related brain areas.

2.1.2 Measures of Neural Entrainment

If RD or DLD are closely related to impaired processing of rhythmic information in the auditory channel more generally, or speech more specifically, one should expect this to be reflected in EEG or MEG measures of neural entrainment. Several measures have emerged to quantify the synchronization of brain oscillations to rhythmic patterns, although no single one of these has been adopted as the accepted standard. Neural entrainment is used as a global term, but distinct measures target distinct aspects of language or pattern processing. Here, we briefly describe the measures typically used to measure neural entrainment. *The Auditory Steady-State Response (ASSR)* measures phase-locking of the electrophysiological response to the temporal envelope of auditory stimuli (Picton et al., 2003). The degree of ASSR synchronization is generally measured via signal-to-noise ratio (SNR; DeVos et al., 2020; Lizarazu et al., 2021b). *Inter-Trial Phase Coherence (ITC),* also referred to as Phase Locking Value, is a measure of event-related phase-locking (Tallon-Baudry et al., 1996), or how well the phase of the neural oscillations follows the phase of the auditory signal at different frequencies over time. Relatedly, *cross-correlation* is used to estimate both amplitude and phase synchronization between neural oscillations and the auditory signal in the time domain. If the magnitude of the correlation coefficient is large, there is a high degree of similarity between the signals. Phase-locking precision is the maximum correlation across lags and phase-locking timing is its corresponding lag (Abrams et al., 2009; Lizarazu et al., 2021b). Similar to cross-correlation, *phase coherence* estimates the phase synchronization between neural oscillations and the envelope of the stimuli by quantifying the strength of oscillatory alignment between the two signals across a range of frequencies (Lizarazu et al., 2021b). *Phase lagged coherence* is the alignment of the phases across different time lags, which allows for a more flexible measurement of phase coherence (Mandke et al., 2022). *Preferred phase* is the phase-locking of phase angles, and *phase consistency* is the consistency of phase angles across trials (Colling et al., 2017; Keshavarzi et al., 2022; Power et al., 2013). The *Phase of Induced Power* is a measure of induced (non-phase-locked) power (Chang et al., 2021), which is thought to reflect temporal prediction since power fluctuations are seen as a representation of entrainment to the beat (Snyder & Large, 2005).

More recently, predictive machine learning models have been used to quantify neural entrainment by more directly linking neural responses to acoustic-phonetic characteristics of the stimuli (Crosse et al., 2016). For forward encoding models, linear regression models are fit to predict how well the EEG neural activity reflects the encoding of certain speech features. The set of weights from the linear regression is referred to as *multivariate Temporal Response Functions* (mTRFs), which estimates the brain's linear mapping between the stimulus feature(s) and the neural response. Encoding models can be used to quantify how well an individual's EEG responses can be predicted from the acoustic or phonetic content of the stimulus. In backward models, a decoder can be trained to reconstruct the acoustic or linguistic form of a speech signal based on an individual's EEG trace. The approach is useful in estimating the extent to which an individual's neural responses are accurately tracking the form and content of auditory speech information.

Neural entrainment can also be analyzed by looking at how different brain regions communicate with each other. Since ITC and coherence compare the synchronization between two signals, they can also be used to measure neural entrainment between different brain regions (e.g., Han et al., 2012). Some studies also use a measure of *Inter-Hemispheric Phase Synchronization (IHPS)*, which estimates the synchronization between left and right auditory regions to the auditory stimulus (Lizarazu et al., 2021b). Connectivity between brain regions can also be measured using the *Phase Lag Index (PLI)*, a measure of the asymmetry of the distribution of phase differences between the neural and auditory signals (Stam et al., 2007; Zhang et al., 2022). Asymmetry in the distribution indicates phase synchronization between the signals. Finally, graph theory is used to look at the topological organization of brain networks during neural entrainment. In this case, connectivity is operationalized as the synchronization of EEG responses across electrodes (Ismail & Karwowski, 2020). Each electrode is coded as a node in a graph, where connectivity among these nodes is computed based on their synchronization within a given frequency range. Graph theoretic measures can then be used to quantify connectivity weights among all nodes in the graph (Molinaro et al., 2016). *Degree* is the number of connections to or from a node above a certain threshold of synchronization, and *strength* is the sum of the weights of the connections to a node. *Global efficiency* measures how efficiently information is transmitted in a network (Latora and Marchiori, 2001). *Network topology* uses a minimum spanning tree in which path-like topology indicates maximal segregation and a star-like topology indicates maximal integration (Stam et al., 2014).

In sum, this range of methods can be used to quantify neural entrainment. Each could provide researchers with various ways to measure the different aspects of neural entrainment to auditory stimuli, although no single measure has emerged as the best outright marker of language processing.

2.1.3 Current Study

This systematic review summarizes the existing research on neural entrainment as it relates to RD and DLD. Comparing these individuals to their typically developing (TD) peers may help us better understand the neurocognitive underpinnings of RD and DLD, and perhaps validate the use of rhythm-based interventions to improve outcomes in these individuals. A significant challenge to this goal is the diversity of the frequency bands that might be implicated in either disorder and the variety of neural measures being deployed to explore them. This review summarizes research into delta, theta, alpha, beta, and gamma frequency bands, in response to different types of stimuli. The boundaries of these bands may differ across studies; therefore, the interpretation of the frequency bands in the present study will be based on the frequency ranges defined by Luck (2014; as described above). Since diagnostic criteria for RD and DLD have changed over time and may be arbitrarily different due to location or lab, we included studies with a range of diagnostic criteria. This review also includes studies conducted on children, adolescents, and adults to understand whether neural entrainment between groups changes with age.

This is not the first systematic review of its kind; Gaudet et al. (2020) conducted a systematic review specifically examining functional brain connectivity (e.g., coherence, PLV) in TD children and children with or at high risk of DLD (including autism spectrum disorder, prematurity). Our aim is somewhat broader, by examining a wider range of EEG measures and stimulation paradigms. We also extend our literature search to individuals with RD, given the commonalities between the two disorders. Unlike the previous review, we did not search for populations that were at-risk for DLD or RD since differences in neural entrainment between these groups and TD individuals may be driven by the underlying disorder and not language functioning per se (Gaudet et al., 2020). Since multiple studies have found that those with RD and DLD have impairments in language, reading, phonemic awareness, and rapid automatized naming (RAN; see Hulme & Snowling, 2016 for a review), we also summarized correlations between those areas of impairments and neural entrainment.

2.2 Methods

2.2.1 Protocol and Registration

This review follows the Preferred Reporting Items for Systematic review and Meta-Analysis (PRISMA) updated guidelines (Page et al., 2020). Methods were preregistered on the Open Science Framework (https://osf.io/xs2he).

2.2.2 Eligibility Criteria

The following criteria had to be met to be included in this review:

1. Compare typically developing adults or children to individuals with RD and/or DLD.
    - Participants who were considered to have poor language or reading abilities were also included if there was no official diagnosis. Diagnosis of the included participants was determined by the authors of the specific study.
    - Studies were excluded if they only included samples with RD or DLD that were fully comorbid with other developmental disorders (e.g., ADHD, autism).
2. The study had to report analyses assessing neural entrainment. The neural measure had to be an EEG or MEG frequency domain or time-frequency domain measure. This includes, but is not limited to, measures of coherence, phase-locking, and speech envelope encoding.
3. The study had to report original empirical findings (not be review, meta-analyses, books).
4. Had to be available in English.
5. Were not case studies with fewer than five participants.

2.2.3 Information Sources and Search Strategy

An initial search on Google Scholar was conducted to determine whether a systematic review had already been conducted on the topic. If not, a quick overview of the results was conducted to determine whether there were at least 10 articles on the topic to conduct a systematic review. Five databases were used to conduct the search: Web of Science, PsycInfo (ProQuest), Dissertations and Theses (ProQuest), PubMed, and Scopus. The initial search was conducted on May 19, 2021, and a secondary search was conducted on August 25, 2022. The following is an example of the Boolean syntax used to find relevant articles in each database:

(“rhythmic track*” or “entrainment” or “phase coherence” or “cortical track*” or “speech track*” or “phase lock*” or “speech envelope”) AND (“reading dis*” or dyslexia or “reading impair*” or “reading delay*” or “language impair*” or “language dis*” or “language delay*” or “poor read*” or “poor language”)

The first half of the Boolean search was conducted on entire documents and the second half only search titles and abstracts. The terms related to EEG or MEG were excluded from the Boolean search as some articles may not have these terms in the title or abstract. Rather, they may use the term for the neural entrainment measure.

2.2.4 Selection Process

Once the searches were complete, the articles were uploaded onto Covidence, a systematic review management tool (Covidence, 2020). Duplicate articles were eliminated automatically upon upload. Two reviewers independently reviewed and selected the articles based on the inclusion and exclusion criteria. Reviewers first screened the abstracts and titles, then screened full texts. Any disagreements about inclusion of studies were resolved by a third reviewer.

2.2.5 Data Collection Process and Data Items

Key information about each article was extracted based on the variables listed below.

- Experiment (a paper might report more than one experiment)
- Study design (i.e., cross-sectional, or longitudinal)
- Publication information (author names, title, year of publication)
- The country in which the study took place.
- Total sample size, including sample size in each group.
- Gender split (M/F)
- Mean and SD of age of participants (years). If this information was not available, an age range was used.
- Language of the study/participants.
- Information about DLD/RD diagnosis or inclusion criteria of these groups.
- The neural entrainment measures used, including whether EEG or MEG was used, which system was used to record neural entrainment, and number of electrodes.
- Information about stimuli.
- Frequency ranges investigated.
- Results (M, SD and/or test statistic and/or effect size).
- Other behavioural or neural measures used.
- If provided, correlations between E/MEG neural entrainment and behavioural measures related to reading or language disability status were extracted.

Specifically reading, phonological awareness, letter-sound knowledge, language scores and RAN.

2.2.6 Effect Measure

The standardized mean difference between the typically developing and RD/DLD groups was calculated for each article that included the relevant statistics. The R package *dmetar* was used to calculate Hedges' *g* and the standard error (Harrer et al., 2021). Positive effect sizes represent greater effects (i.e., greater scores) for the typically developing group. If an effect size was calculated for the right and left hemispheres, the mean effect size was aggregated using the MAd package (Del Re & Hoyt, 2010). This follows Borenstein et al. (2009) and Cooper et al.'s (2009) recommended approach to calculating mean effect sizes and variances. A correlation of 1.0 between the effect sizes was assumed, which is the more conservative approach for calculating variance. As the correlation approaches 0, it underestimates the variance and inflates Type I error (Borenstein et al., 2009; Scammacca et al., 2014).

2.3 Results

2.3.1 Study Selection

The PRISMA flowchart (see Figure 2.2.1) details the selection process from title and abstract screening to full-text screening, and the reasons for excluding articles. Inter-rater reliability at the title and abstract stage (proportion of agreement = .95, k = .85) and the full-text review stage (proportion of agreement = .93, k = .84), signify almost perfect agreement (Cohen, 1960).

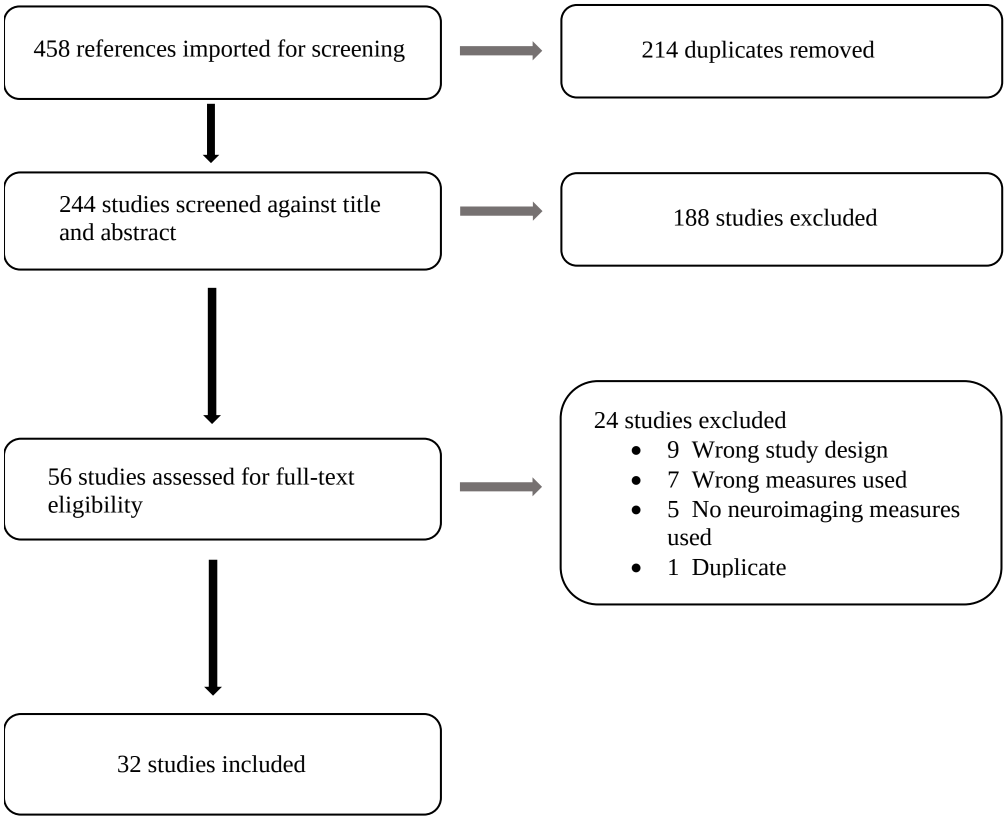

Figure 2.2.1. PRISMA flowchart for article selection at each screening stage.

2.3.2 Study Characteristics

Error! Reference source not found. summarizes the article information, including population focus, diagnosis of RD or DLD (or division of poor vs good readers), and demographic information. Thirty-two studies were included in the review, of which thirty looked at RD and two looked at DLD. There were three cases in which two publications reported data from the same or overlapping dataset (Study ID (SID) 26 and 4; SID 27 and 5; SID 31 and 32). The results from each study are reported since they used different analyses to measure neural entrainment; however, we make sure to note when studies report from the same participants. The age group with the biggest focus was 5- to -12-year-olds followed by 20- to -29-year-olds. There was a wide range of inclusion criteria for the RD and DLD groups, with seventeen studies requiring official diagnoses or history of a diagnosis of RD or DLD.

Table 2.1. Description of articles included in the review, including demographic information.

Study ID	References	Group	Diagnosis	Language	TD n (m/f)	Non-TD n (m/f)	Mean age TD in years (SD)	Mean age non-TD in years (SD)
1	Abrams et al., 2009	Poor readers	Bottom third based on reading scores	English	8	8	12 (1.5)	12.8 (2.0)
2	Colling et al., 2017	Dyslexia (RD)	Statement of dyslexia and/or severe literacy and phonological deficits	English	13 (7/6)	11 (4/7)	10.08 (.66)	9.94 (.94)
3	De Vos et al., 2020	RD	Severe and persistent problems, reading and spelling scores below the 10th percentile	Dutch	55 (34/21); 48 (31/17)	15 (8/7); 15 (7/8)	Beginning reader: 7.03 (.25); 7.03 (.25) Advanced reader: 9.08 (.33); 9.08 (.25)	Beginning reader: 7.03 (.25) Advanced reader: 9.08 (.25)
4	De Vos et al., 2017a	RD	Formal diagnosis, or life-long history of reading problems and reading below the 10th percentile	Dutch	21 (10/11)	32 (15/17)	14.75 (.25)	14.66 (.33)
5	De Vos et al., 2017b	RD	Severe and persistent problems, reading below 10th percentile or spelling below 10th percentile and reading below 25th percentile	Dutch	54 (35/19)	14 (6/8)	5.16 (.25) 7.08 (.25) 9.08 (.33)	5.08 (.25) 7.08 (.25) 9.08 (.25)
6	Di Liberto et al., 2018	RD	1.5 SD below mean in phonological processing and reading	English	45 (25/20)	25 (17/8)	6 to 12	

7	Dushanova et al., 2020	RD	Evaluation of developmental dyslexia and dysorthography	Bulgarian	20 (12/8)	26 (17/9)	8 to 9	
8	Fiveash et al., 2020	RD	Diagnosis of dyslexia and speech therapy for at least two years in childhood	French	12 (5/7)	13 (6/7)	22.42 (2.15)	23.2 (2.95)
9	Hämäläinen et al., 2012	RD	Official diagnosis	English	10 (2/8)	11 (6/5)	27.5 (5)	21.9 (3.2)
10	Han et al., 2012	Poor readers	Below the 25th percentile on reading tasks and identified as reading below grade level.	English	10	10	17.2 (1.29)	17.2 (1.24)
11	Heim et al., 2011	DLD	1 SD below mean on at least two language tasks or below 25th percentile on three tasks and a recent history of language therapy	English	18 (9/9)	29 (20/9)	8.02 (.99)	8.05 (1.02)
12	Lehongre et al., 2013	RD	Self-reported history of dyslexia, scored at or below expected level in reading	French	15 (7/8)	17 (9/8)	24.09 (3.54)	23.79 (4.04)
13	Lehongre et al., 2011	RD	History of dyslexia, scored at or below expected level in reading	French	21 (11/10)	23 (14/9)	24.38 (3.85)	24.61 (4.57)
14	Lizarazu et al., 2015	RD	Formal diagnosis of dyslexia	Spanish	10 (5/5); 11 (4/7)	10 (6/4); 11(5/6)	8 to 14.3; 17.3 to 44.9	
15	Lizarazu et al., 2021a	RD	Formal diagnosis of dyslexia	Spanish	18 (8/10)	18 (9/9)	16.8 to 44.9	17.2 to 44.9
16	Lizarazu et al., 2021b	RD	History of reading difficulties and reading score below 10th percentile	French	20 (8/12)	19 (11/8)	19 to 40.7	
17	Molinaro et al., 2016	RD	Formal diagnosis of dyslexia	Spanish	20 (10/10)	20 (9/11)	11.6; 32.5	11.08; 29.75

18	Poelmans et al., 2012	RD	Formal diagnosis of dyslexia	Dutch	30	30	21.4 (2.7)	21.5 (2.7)
19	Power et al., 2013	RD	History of dyslexia	English	21	11	13.80 (1.06)	13.89 (1.14)
20	Soltész et al., 2013	RD	Childhood diagnosis of dyslexia	English	14 (4/10)	13 (8/5)	27.5 (5.5)	25.8 (6.9)
21	Van Hirtum et al., 2019	RD	Formal diagnosis of dyslexia	Dutch	18 (8/10)	20 (10/10)	18 to 25	18 to 25
22	Halliday et al., 2014	RD	Diagnosis of dyslexia	English	20 (10/10)	20 (15/5)	9.06 (.99); 12.32 (.74)	8.96 (1.08); 11.93 (1.19)
23	Heim et al., 2013	DLD	Formally diagnosed as language impaired	English	12 (6/6)	21 (15/6)	8.24(.92)	8.04(.95)
24	Chang et al., 2021	RD	Saw a speech therapist for dyslexia and reading training during childhood	French	13 (6/7)	13 (6/7)	22.5 (2.07)	23.2 (2.95)
25	Destoky et al., 2022	RD	Diagnosis of dyslexia and at least 2 years behind in reading.	French	26 (13/13) ; 26 (15/11)	26 (9/17)	TD-age: 10 (1) TD-read: 7.8(.6)	10.2 (1.1)
26	Granados Barbero et al., 2021a	RD	Based on history of reading problems and current reading performance	Dutch	22 (10/12)	32 (15/17)	14.75	14.66
27	Granados Barbero et al., 2022	RD	Severe and persistent reading or spelling problems, score below the 10th on tests	Dutch	21	21	5 to 9	
28	Keshavarzi et al., 2022	RD	10 SD below the norm on at least two reading and spelling tests.	English	21	30	9.11 (.45)	9.23 (.47)
29	Mandke et al., 2022	RD	Schools' Special Educational Needs coordinators	English	20 (15/5)	19 (10/9)	8.81 (.6)	9.66 (.77)
30	Rufener & Zaehle, 2021	RD	Official diagnosis of dyslexia	German	26 (16/10)	32 (24/8)	12.4 (2.25)	11.5 (2.31)

31	Zhang et al., 2022	RD	Did not specify	Dutch	18 (6/12)	18 (4/14)	20.8 (2.26)	23.9 (4.01)
32	Zhang et al., 2021	RD	Official diagnosis of dyslexia	Dutch	18 (6/12)	18 (4/14)	20.8 (2.26)	23.9 (4.00)

Table 2.2 summarizes the neural entrainment analyses, study design, stimuli, number of electrodes, and the frequencies of interest for each study. EEG was used in 72% of studies while the others used MEG. The number of channels recorded for the EEG systems had a large range from 10 to 129 electrodes, with 64 electrodes being the most popular (used in 10 studies). The type of system used also varied widely which included, but was not limited to, BioSemi ActiveTwo, EGI (Electrical Geodesics Inc.), and Brain Products ActiCap (Brain Products GmbH, Germany) systems. All MEG studies used Elekta Neuromag/MEGIN systems (Helsinki, Finland). There was also more consistency in the number of MEG channels used, with five studies using 306 channels, three using 102 channels, one using 151 channels, and another using 62. As for study design, most studies were cross-sectional, with three studies being longitudinal (SID 3, 5, 27). If there were multiple age groups, data from each age group was included in the summary of results (SID 3, 5, 27).

Table 2.2. Methodological information of studies included in the review.

Study ID	Analyses	Stimuli	System (number of channels)	Frequencies of interest
1	Cross-correlation (Phase-locking precision, phase-locking timing, phase-locking magnitude)	Conversational, compressed, and clear speech	EEG (31)	Syllable rate (delta)
2	Cross-correlation, auditory steady-state response (referred to as	Amplitude modulated (AM) pure tone	EEG (128)	2.4 Hz (Delta)

	steady-state evoked potentials)			
3	ASSR (SNR)	AM speech-weighted noise	EEG (64)	80 Hz (Upper gamma)
4	ASSR (SNR)	AM speech-weighted noise	EEG (64)	4, 10, 20, 40 Hz (Theta, alpha, beta, lower-gamma)
5	ASSR (SNR)	AM speech-weighted noise	EEG (64)	4, 20 Hz (theta, beta)
6	Forward encoding model	Speech (Audio-story with cartoon)	EEG (129)	1-4 Hz (Delta), 4-8 Hz (theta), 1-8 Hz
7	Coherence	Words/pseudowords presented at rhythmic rate	EEG (40)	2-4 Hz (delta), 12.5-22 Hz (beta), 25-35 Hz (low gamma), and 35-80 Hz (high gamma)
8	Coherence	Speech (regular and irregular rhythms with sentences)	EEG (95)	2, 4, 8 Hz (delta, theta, alpha)
9	ITC	White noise	MEG (306)	2, 4, 10, 20 Hz (delta, theta, alpha, beta)
10	ITC between regions	Speech (sentences with sentence-terminal critical word. Congruent and incongruent sentences, phonologically similar or dissimilar to target words)	MEG (306)	4-8 Hz (100-250 ms; theta), 30-45 (200-350 ms; low gamma), 8-12 (350-550; alpha), 30-45 Hz (400-600 ms; low gamma 2)
11	ITC	Repeated tones and oddball deviants	EEG (64)	20-80 Hz (Gamma)
12	Power time courses z-scored	Speech (scientific documentary on ecology)	EEG and fMRI (62)	1-3 Hz (delta), 4-7 Hz (theta), 25-35 Hz (low gamma)

13	ASSR	White noise	MEG (151)	10-80 Hz, with a focus on 25-35 Hz, > 50 Hz (gamma)
14	ITC	White noise	MEG (102)	2, 4, 7, 30, 60 Hz (delta, theta, alpha, beta, gamma)
15	ITC	Speech (meaningful semantically neutral sentences)	MEG (102)	Delta
16	ASSR (SNR), ITC, IHPS, coherence, cross-correlation	AM white noise, forward and backward speech	MEG (306)	2 Hz (delta), 5 Hz (theta), 30 Hz (beta), alpha, gamma
17	Coherence, graph theory	Speech (meaningful sentences)	MEG (102)	.5-1 Hz (delta), 5.8-6.3 Hz (theta)
18	ASSR (SNR), inter- and intra-hemispheric coherence	Continuous AM speech-weighted noise	EEG (10)	4, 20, 80 Hz (theta, beta, upper gamma)
19	ITC, Cross-correlation	Multiple repetitions of the syllable “ba”	EEG (65)	delta (~2 Hz), theta (~4 Hz)
20	ITC	Continuous tones	EEG (129)	1.5, 2 Hz (delta)
21	ASSR (SNR)	Continuous AM one-octave white noise	EEG (64)	4, 10, 20, 40 Hz (theta, alpha, beta, lower gamma)
22	ITC	Repeated tones and oddball deviants	EEG (28)	5-20 Hz, with a focus on 4-7 Hz (theta)
23	ITC	Repeated tones and oddball deviants	EEG (64)	29-52 Hz (Gamma)
24	Phase of induced power	Piano tone (C4)	EEG (95)	15-25 Hz (Beta)

25	Backward model; cortical tracking of speech (CTS)	Speech with no noise, non-speech noise, babble noise	MEG (306)	.2-1.5 Hz (phrasal ; delta) and 2-8 Hz (syllabic ; theta)
26	ASSR (SNR), coherence between components	AM speech-weighted noise	EEG (64)	Theta, alpha, beta, low gamma
27	ASSR (SNR), coherence between components	AM speech-weighted noise	EEG (64)	4 and 20 Hz (theta, beta)
28	Phase entrainment consistency, preferred phase	Rhythmic sequence of "ba" with visual cues	EEG (128)	.5-4Hz (delta), 4-8 Hz (theta), 8-12 Hz (alpha)
29	Coherence, ITC between regions, graph theory (global efficiency)	Speech (10 min recording of a children's book)	MEG (306)	< 5Hz (delta; stress .9-2.5 and syllable 2.5-5); 5-9 Hz (theta; sub-beat); 12-40 Hz (beta-gamma; phoneme)
30	ASSR	AM pure tones	EEG (21)	Gamma
31	Phase lag index, graph theory (network topology)	Random stream of 12 Dutch syllables and real stream with 4 trisyllabic real words	EEG (64)	.5-4 Hz (delta), 4-8 Hz (theta), 8-13 Hz (alpha), 13-30 Hz (beta)
32	ITC	Random stream of 12 Dutch syllables, real stream with 4 trisyllabic real words and a pseudoword stream of four trisyllabic pseudowords	EEG (64)	Delta (word: 1.1 Hz, syllable: 3.3 Hz)

As for the frequency bands examined, 17 studies looked at delta, 20 at theta, 8 at alpha, 13 at beta, 14 at gamma (2 of which looked at DLD). The frequency ranges across studies were not all consistent. Although we tried to fit each study's frequency range within our specified frequency bands (following Luck et al., 2014), some of the ranges overlapped. We define delta as under 4 Hz, theta as 4-7 Hz, alpha as 8-12 Hz, beta as 13-30 Hz, and gamma as over 30 Hz. Multiple studies defined low gamma as 25-35 Hz (SID 7; SID 13; SID 14). Gamma was also defined as 20-80 Hz (SID 11; SID 23). SID 25 defined their syllabic band as 2-8 Hz, which overlapped with delta, theta, and alpha. Since theta is most associated with syllabic processing, we included this band in our interpretation of theta. There is also the most overlap with their syllabic band and theta. SID 29 used a data-driven approach to segment their frequency bands. Their stress (.9-2.5 Hz) and syllable (2.5-5 Hz) frequency bands were both considered delta since most of the syllable band overlapped with delta. The sub-beat band (5-9 Hz) was considered theta since again, there was more overlap with this frequency band than with alpha. The phoneme rate (12-40 Hz) overlapped significantly with beta and gamma. Ultimately, it was decided to consider this band as beta since there was more overlap with our definition of beta vs. gamma. Another thing to consider is that some studies focused on one frequency within our ranges, which could again impact the interpretation of the results.

There was also a broad range of stimuli used to elicit neural entrainment. Table 2.3 summarizes how many studies used each stimulus type. Note that some studies used multiple types of stimuli.

Table 2.2. Overview of the stimuli used. Number of studies (percent) for each stimuli type.

Stimuli	n (%)
Connected speech (sentences, narrative)	10 (31)
Speech-weighted noise	6 (19)
White noise	5 (16)
Word repetition	3 (9)
Pseudoword repetition	3 (9)

Pure tones	3 (9)
Repeated tones and deviants	3 (9)
Same-syllable repetition	2 (6)

Studies used either passive or active listening conditions. In a passive condition, participants simply had to listen to the stimuli. In an active condition, participants were asked to make a response during or after stimulus presentation (e.g., oddball detection and comprehension questions). The most frequently used stimulus type was connected speech, followed by speech-weighted and white noise. The type of connected speech varied, but generally, unrelated sentences or stories with a narrative were presented. Some studies also included background noise, compressed speech, and backward speech conditions. As for noise, participants passively listened to continuous speech-weighted or AM white noise (for example, they could be 100% AM at 4, 10, 20 Hz) to simulate listening to speech-related frequencies.

Table 2.4 summarizes the number of studies using each type of analysis, with some studies reporting multiple analyses. Four studies also measured laterality (or lateralization) index, calculated by subtracting the neural entrainment value in the LH from the RH and baseline correcting with the sum of both. Positive values indicate right-dominance and negative values left-dominance.

Table 2.3. Overview of the neural entrainment analyses used.

Connectivity analysis	n (%)
ITC	13 (41)+
ASSR (SNR)	11 (34)
Coherence	8 (25)
Cross-correlation	4 (13)
Graph theory	3 (9)
Preferred phase	3 (9)
Phase consistency	3 (9)
PLI	1 (3)
IHPS	1 (3)
Phase of induced power	1 (3)
Forward encoding model	1 (3)
Backward model (CTS)	1 (3)
EEG z-score transformed power	1 (3)

Notes. + = of the studies included, two focused on participants with DLD.

2.3.3 Synthesis of Results

We summarize the results for each frequency band in Tables 2.5-2.9. Effect sizes are included in each table representing each frequency band, if possible. See Appendix A for a more detailed breakdown of the findings for each frequency band. Correlations between the EEG neural entrainment and behavioural measures of reading, language, phonological processing, and RAN are summarized in Table 2.10. A detailed description of the correlations is also included in the appendix. Reading measures include reading passages (reading time and accuracy), the Test of Word Reading Efficiency (TOWRE; Torgesen et al., 1999) which looks at sight-word reading and nonword reading (phonemic decoding), language measures include the Comprehensive Evaluation of Language Fundamentals (CELF; Semel et al., 2006), and receptive vocabulary, phonological processing measures include the Comprehensive Test of Phonological Processing (CTOPP; Wagner et al., 2013), phonological short-term memory, phoneme deletion, and rhyme judgement, and RAN includes rapid automatized naming of digits, colours, and pictures.

Table 2.4. Results for the delta frequency band, including effect sizes and lateralization. All delta results are between participants with and without RD.

Study ID	Measure	Delta	Effect	Notes and other findings
1	Cross-correlation	Clear & conversational: n.s. Compressed: rmax: TD > RD in RH Later lags in RH and earlier lags in LH for RD vs TD.	rmax: Clear speech:.00(.5) Conversational speech: .21(.50)	RH dominance for the clear and conversational conditions in both groups. Phase-locking magnitude: TD > responses in RH and RD more symmetric in compressed condition
2	ASSR	n.s.	Right-hand tapping: -.39(.41) Left-hand tapping: -.56(.42) Auditory-only: -.33(.41)	Conditions: right-hand tapping, left-hand tapping, auditory-only 2.4 Hz reflects beat entrainment
	Cross-correlation	rmax: n.s. Earlier preferred phase for RD Phase consistency: n.s.	rmax: .50(.42) Phase lag: -1.05(.44)	
6	Forward encoding models	TD > RD		
7	Coherence	Words: n.s. for TD & RDNoPho in more areas, TD > RDNoPho at 4 Hz in ITG and RH auditory cortex, TD > RDPho at 2 Hz and under 4Hz		*Simplification of results. More details found for specific electrodes in article. RDNoPho = RD with no phonological deficits. RDPho = RD with phonological deficits.
		Pseudowords: TD > RDNoPho at 2–4 Hz in right auditory cortex, TD > RD in right inferior frontal cortex, TD < RDNoPho in left inferior frontal and auditory cortices		

8	Coherence	Regular rhythm: n.s. 2.3-2.5 Hz for irregular rhythms: TD > RD		
9	ITC	TD > RD	RH: .83(.46)	TD had better ITC in right auditory cortex, and RD more bilateral
12	Correlations between EEG z-score transformed power and BOLD	n.s.		Stronger correlations for RH vs LH in RD
15	ITC	TD > RD in LH from ~.15 sec to ~.65 sec after edge onset		
16	ASSR (SNR)	n.s.	White noise: .06(.30)	LI: SNR right lateralized at 2 Hz. ITC right lateralized at 2 Hz Cross-correlation: phase rmax right-lateralized at 2 Hz. Amplitude rmax bilateral at 2 Hz for RD and right-lateralized at 2Hz for TD. LH and RH effect sizes combined.
	ITC		White noise: -.30(.30)	
	IHPS		White noise: .24(.32)	
	Coherence		Forward and backward speech: 0(.32)	
	Cross-correlation		Phase rmax: White noise: -.49(.11) Speech: -.21 (.10) Phase lag: White noise: -.39(.05) Speech: .19(.10) Amplitude rmax: White noise: 0 (.10) Speech: -.07(.10) Amplitude lag: White noise: -.09(.10) Speech: .78(.11)	
17	Coherence	TD > RD		
	Graph Theory	TD > RD out-strength profile of right auditory cortex TD > RD for inward strength in left IFG		TD had rightward asymmetry. RD had reduced connectivity between right auditory cortex and left IFG
19	ITC	n.s.	.26(.37)	
	Cross-correlation	n.s. TD have later peak lags than RD	rmax = .63(.38) Phase lag: .88(.39) Preferred phase: 1.41(.44)	

		Preferred phase only differed at Cz		
20	ITC	TD > RD	.60(.36)	
25	CTS	TD-age > RD & TD-read for babble noise n.s. for non-speech noise and noiseless conditions		
28	Phase Consistency	TD > RD	.67(.29)	
	Preferred Phase	RD is twice the rate of TD		
29	Coherence: lagged coherence	Stress (.9-2.5 Hz): TD > RD Syllable (2.5-5 Hz) : TD > RD		TD had more uniform, bilateral connectivity and RD had overall reduced functional connectivity.
	ITC between regions	TD > RD; rightward asymmetry for RD		
	Global efficiency	TD > RD		
31	Phase lag index	n.s.	.19 (.33)	
	Network topology	n.s.		
32	ITC	1.1 Hz: TD > RD 3.3 Hz: n.s.	Structured stream ITC max: .74 (.35) Real word ITC max: -.09 (.33)	No gains in pseudoword tracking for RD over time

Table 2.5. Results for the theta frequency band, including effect sizes and lateralization. All theta results are between participants with and without RD.

Study ID	Measure	Theta	Effect	Notes and other findings
4	ASSR (SNR)	n.s.	.49(.28)	RD had smaller 3-5 Hz amplitudes compared to TD
5	ASSR (SNR)	n.s.		
6	Forward encoding models	1-8 Hz: TD > RD in frontal, occipital and RH		Broader scalp areas in delta vs theta Effect was mainly driven by delta
8	Coherence	n.s.		
9	ITC	n.s.		TD had better ITC in right auditory cortex, and RD is more bilateral

10	ITC between regions	n.s.		
12	Correlations between EEG z-score transformed power and BOLD	n.s.		Right dominance in TD
14	ITC	4 Hz: TD < RD 7 Hz: n.s.	4 Hz: -.59(.32) for RH	LI: Stronger in RH in TD and bilateral in RD
16	ASSR (SNR)	n.s.	White noise: 3.33(.31)	LI: Nonspeech: SNR bilateral at 5 Hz. ITCs right lateralized at 5 Hz. Speech: coherence values were right lateralized for forward speech and bilateral for backward speech. Cross-correlation: nonspeech: phase and amplitude bilateral at 5 Hz for TD and RD. LH and RH effect sizes combined, as well as forward and backward speech for cross-correlations.
	ITC	n.s.	White noise: .01(.30)	
	IHPS	n.s.	White noise: .16(.32)	
	Coherence	n.s., TD > RD for forward speech in RH	forward: .49(.31); backward: 0(.32)	
	Cross-correlation	n.s.	Phase rmax: White noise: -.31(.11) Speech: -.74(.11) Phase lag: White noise: .18(.10) Speech: .00(0.10) Amplitude rmax: White noise: 0(.32) Speech: .26(.10) Amplitude lag: White noise: .14(.10) Speech: .00(.10)	
17	Coherence	n.s.		
18	ASSR (SNR)	n.s.	.20(.26)	At parietal electrodes, ASSR in RH > LH Coherence in RH > LH
	Coherence	n.s.	inter: .17(.26) intra: .03(.26)	
19	Preferred phase	n.s.		Cross-correlation: TD have longer peak lags than RD in delta-theta
	ITC	n.s.	.66(.38)	
21	ASSR (SNR)	n.s.		
22	ITC	Younger: TD < RD to small deviants n.s. to large deviants Older: TD < RD	Younger: Large deviant: .62(.32) Small deviant: -1.47(.36) Older: Large deviant: -1.24(.35) Small deviant: -1.47(.36)	

25	CTS	TD-read < RD TD-age vs. RD n.s.	TD-read vs RD: -.70(.29) TD-age vs RD: .23(.28)	TD-age > RD in RH
26	ASSR (SNR)	TD < RD both components TD < RD for left ear		LI: Right lateralization in RD for right ear stimulation
	Coherence between components	TD < RD right ear only		This is a measure of neural connectivity
27	ASSR (SNR)	n.s. at 7 years. TD > RD at 5 and 9 years		LI: 4 Hz: RH preference across age. Right lateralization TD > RD at 5 and 7 years.
	Coherence between components	TD > RD at 5 and 9 years TD < RD at 7 years		
28	Phase entrainment consistency	n.s.	-.06(.28)	
29	Coherence	Sub-beat (5-9 Hz): TD > RD in right postcentral gyrus		
31	Phase lag index	n.s.	.03 (.33)	
	Network topology	n.s.		Larger shift towards a more integrated topology during word tracking relative to random syllable tracking in RD vs. TD More reliance on right frontal electrodes for word tracking in RD

Table 2.6. Results for the alpha frequency band, including effect sizes and lateralization. All alpha results are between participants with and without RD.

Study ID	Measure	Alpha	Effect	Notes and other findings
4	ASSR (SNR)	TD > RD	.61(.29)	
9	ITC	n.s.	Overall: -.83(.46) LH: -1.07(.47)	

10	ITC between regions	n.s.		
16	Cross-correlation	n.s.	Amplitude rmax: Speech: .04(.10) Amplitude lag: Speech: .05(.10)	
21	ASSR (SNR)	n.s. TD > RD for RT10 and RT30	RT10 and RT30: .38(.33)	Had baseline condition, rise times at 10 and 30 ms
26	ASSR (SNR)	TD > RD for left ear only component 1 n.s. for component 2		
	Coherence between components	TD < RD for right ear TD > RD for left ear		
28	Phase entrainment consistency	n.s.	.20 (.29)	
31	Phase lag index	n.s.	.27(.33)	
	Network topology	n.s.		

Table 2.7. Results for the beta frequency band, including effect sizes and lateralization. All beta results are between participants with and without RD.

Study ID	Measure	Beta	Effect	Notes and other findings
4	ASSR (SNR)	n.s. TD < RD for left and right ear stimulation	.36(.28)	
5	ASSR (SNR)	TD < RD Age 5: n.s.	-.65(.31)	
7	Coherence	TD < RD in RH at 20 Hz for words TD > RD for words TD > RD in RH for pseudowords	RH: PT: -1.47(.37) Middle occipital gyrus: -1.16(.34)	More widespread entrainment for TD
9	ITC	n.s.		More dominant widespread entrainment in TD
14	ITC	TD < RD RH, n.s. LH and overall	right: .77(.32)	

			left: 0(.31), overall: .38(.29)	
16	ASSR (SNR)	n.s.	1.57(.30)	LI: Nonspeech: SNR bilateral at 30 Hz. ITCs right lateralized at 30 Hz. Cross-correlation: Nonspeech: Phase bilateral at 30 Hz. Amplitude left-lateralized in TD, bilateral in RD. LH and RH effect sizes combined.
	ITC	n.s.	0(.32)	
	IHPS	n.s.	.22(.32)	
	Amplitude Cross-correlation	n.s.	Phase rmax: White noise: 0(.10) Phase lag: White noise: -.09(.10) Amplitude rmax: Speech: .19(.11) White noise: 0 (.10) Amplitude lag: White noise: -.61(.11) Speech: .38(.10)	
18	ASSR (SNR)	n.s.	.39(.26)	TD > RD in LH
	Coherence	Intrahemispheric: TD > RD	.54(.26)	
21	ASSR (SNR)	n.s. TD > RD for RT30	RT30: .35(.33)	Had baseline condition, rise times at 10 and 30 ms
24	Phase of induced power	Different at right auditory cortex	right: 1.36(.44) left: .71 (.41)	Power fluctuations atypical in RD and opposite to TD
26	ASSR (SNR)	TD < RD		LI: Ipsilateral responses for all conditions.
	Coherence between components	TD < RD for right ear only		
27	ASSR (SNR)	n.s. at 7 years. TD < RD at 5 years TD > RD at 9 years		LI: Stronger right lateralization in RD at 5 and 7 years.
	Coherence between components	n.s. at 5 years. TD > RD at 7 years TD < RD at 9 years		
29	Coherence: lagged coherence	TD > RD in occipital region		Lagged coherence was sparse in RD
31	Phase lag index	n.s.	.12 (.33)	

	Network topology	n.s.		

Table 2.8. Results for the gamma frequency band, including effect sizes and lateralization. The last two studies are DLD vs. TD. The remaining are between individuals with RD and TD individuals.

Study ID	Measure	Gamma	Effect	Notes and other findings
3	ASSR (SNR)	TD > RD for beginners n.s. for advanced readers	Beginner: .31(.31) Advanced: .40(.36) Overall: .35(.33)	RH and LH effect sizes combined
4	ASSR (SNR)	n.s.		
7	Coherence	TD < RD at 30 Hz in right PT and STS TD > RD in RH at 30 Hz TD > RDNoPho LH at 30 Hz TD < RD in LH at 40 Hz for words and pseudowords TD < RDNoPho RH dominance at 40 and 48 Hz in auditory cortex TD < RDNoPho in left auditory cortex at 45–65 Hz TD < RDNoPho in PT at 55 Hz TD < RDPho in adjacent STS regions and ITG at 45-65 Hz	PT and adjacent superior temporal sulcus for TD vs RD at 30 Hz: -1.31(.35)	*Simplification of results. More details found for specific electrodes in article
10	ITC between regions	n.s.		30-45 Hz (400-600 ms): Phonologically similar > dissimilar for TD Dissimilar > similar for RD
12	Correlations between	TD > RD in LH		

	EEG z-score transformed power and BOLD			
13	ASSR (SNR)	25-35 Hz: TD > RD in left planum temporale (PT) 40 Hz: TD < RD in RH 50 Hz: TD < RD		TD left-dominant at 25-35 Hz. No left dominance for RD, but right-dominance at 30 Hz in PT.
14	ITC	n.s.		
16	Amplitude Cross-correlation	Amplitude rmax: TD > RD in LH	Amplitude rmax: Speech: -.02(.10) Amplitude lag: Speech: .27(.11)	LH and RH effect sizes combined.
18	ASSR	n.s.	.35(.26)	
	Coherence		inter: .43(.26) intra: .29(.26)	
21	ASSR (SNR)	TD > RD in RH	RH: .30(.33)	
26	ASSR (SNR)	TD < RD		
	Coherence between components	TD < RD for left ear only		
30	ASSR (peak individual gamma frequency)	TD > RD	.86(.28)	
11	ITC	20-80 Hz: TD > DLD for second tone	1.51(.34)	Lower amplitude in RH in passive condition and lower amplitude in LH in active condition
23	ITC	20-80 Hz: TD > DLD for the second tone	1.30(.40)	Greater gain in DLD vs TD Reduced phase-locking in DLD to the second tone

Table 2.9. Correlations between E/MEG neural entrainment and behavioural measures related to language and reading. The “+” symbol indicates a significant positive correlation, the “-“ symbol indicates a significant negative correlation, and “n.s.” indicates no significant correlation.

Study ID	Connectivity measure	Reading	Phonological processing	TOWRE	RAN	Language
1	Precision asymmetry at theta	+	+			
	Timing asymmetry at theta	-	-			
	Magnitude asymmetry at theta	+	+			
2	Auditory-only phase at 2.4 Hz	n.s.	n.s.	n.s.		
	Auditory-only SS-EP power at 2.4 Hz	-	n.s.	-		
4	4 Hz surrounding amplitude	n.s.	n.s.			
	10 Hz response amplitude	n.s	TD: + RD: n.s.			
	20 Hz SNR	n.s.	TD: n.s. RD: +			
5	4 Hz ASSR noise and response amplitude	n.s.	n.s.		n.s.	
	20 Hz ASSR noise amplitude	n.s.	n.s.		n.s.	
	20 Hz ASSR response amplitude	-	-		-	
6	Acoustic and phoneme level model	n.s.	+		n.s.	+
	Phoneme level model	+	+			+
13	Low gamma (25-35 Hz) asymmetry	All: + TD: n.s. RD: n.s.	All: n.s. TD: n.s. RD: -		All: + TD: n.s. RD: +	
	High gamma (45-65 Hz)	n.s.	Verbal WM: -		n.s.	
14	4 Hz LI	TD: + n.s.				

	30-60 Hz LI			Adults: +	Kids: n.s.				
	30 Hz LI	n.s.		n.s.					
15	ITC to speech edges	RD reading time: -		n.s.					
		RD reading accuracy: +							
16	Cross-correlation at 2 Hz right auditory cortex	n.s.		n.s.				n.s.	
	Cross-correlation at 30 Hz left auditory cortex	n.s.		n.s.				n.s.	
17	Delta coherence in right auditory cortex	n.s.		n.s.		n.s.			
	Delta coherence in left IFG					SWE RD: +	PDE: n.s		
18	ASSR 4 Hz			n.s.					
	ASSR 20 Hz			-					
	ASSR 80 Hz			n.s.					
19	Preferred delta phase at Cz auditory-only	+		Phon. STM: n.s.	Phon. del: +	+		n.s.	
	r-value at Cz auditory-only	+		n.s		SWE: n.s.	PDE: +		
	Peak lag at Cz auditory-only	+		Phon. STM: n.s.	Phon. del: +	n.s.			
20	2 Hz ITC	+		+				-	
	1.5 Hz ITC	n.s.		n.s.				n.s.	
21	10 Hz ASSR	n.s.		n.s.				n.s.	
	20 Hz RT-30 SNR	+		n.s.				n.s	
	40 Hz ASSR background activity in RH	-		-				-	

22	ITC 4-7 Hz	Nonword rep: -		SWE: n.s. PDE: -		
25	Phrasal CTS				RH: - LH: n.s. Both: n.s.	
28	Delta- length of resultant vector	n.s.	n.s.	SWE: + PDE: +	Digits: + Pictures: n.s.	
	Theta – length of resultant vector			n.s.	n.s.	
	Delta-preferred phase	n.s.	n.s.		Digits: n.s. Pictures: +	
	Theta-preferred phase	n.s.	n.s.		n.s.	
29[1]	Stress & Syllable AM lagged coherence & global efficiency	n.s.		n.s.		n.s.
30	Individual gamma frequency		+			
31	Difference value of tree hierarchy at beta	n.s.	n.s.			
32	Word-rate ITC for SSmax	n.s.	+		n.s.	
	Word-rate ITC for RWmax		n.s.		Symbol :+ Non-symbol: n.s.	

2.4 Discussion

Our systematic review reveals key differences in neural entrainment in individuals with RD or DLD compared to their TD peers across 32 articles, of which 30 examined RD and 2 examined DLD. The pattern of results and group differences varied widely in most frequency bands depending on the task and neural entrainment methods used.

Below we discuss the findings in relation to theories and past findings of neural entrainment in those with RD or DLD.

2.4.1 Overall Neural Entrainment RD

2.4.1.1 Delta Band

There was the most consensus among measures in the delta-band, reflecting prosodic information, with neural entrainment being greater in TD than RD irrespective of stimuli (Abrams et al., 2009; Di Liberto et al., 2018; Dushanova et al., 2020; Hämäläinen et al., 2012; Keshavarzi et al., 2022; Lizarazu et al., 2021a; Mandke et al., 2022; Molinaro et al., 2016; Soltész et al., 2013). Further, three studies found that individuals with RD had worse entrainment for challenging listening conditions (e.g., compressed speech). Greater delta entrainment was also related to better phonological processing, language, and reading abilities (Di Liberto et al., 2018; Colling et al., 2017; Keshavarzi et al., 2022; Power et al., 2013; Soltész et al., 2013; Zhang et al., 2021). These findings are in line with the Temporal Sampling Framework (TSF, Goswami, 2011). The TSF posits that individuals with RD struggle with temporal processing of linguistic information which is related to impaired neural entrainment of prosodic information. Part of the TSF is the idea that atypical processing of amplitude rise times and modulations may underpin phonological processing difficulties (Goswami, 2018). Indeed, the correlations demonstrate that impaired neural entrainment is related to difficulties in language and reading abilities, especially in phonological processing.

2.4.1.2 Theta Band

The pattern of results was more varied in the theta band, which reflects syllabic processing, with results varying based on the methods used. Just under half of the studies found no differences in neural entrainment between TD and RD (De Vos et al., 2017a, 2017b; Di Liberto et al., 2018; Fiveash et al., 2020; Han et al., 2012; Keshavarzi et al., 2022; Molinaro et al., 2016; Poelmans et al., 2012; Power et al., 2013; Van Hirtum et al., 2019). In studies that did find differences between groups (Destoky et al., 2022; Granados Barbero et al., 2021; Halliday et al., 2014; Lizarazu et al., 2015, 2021b; Mandke et al., 2022), the results demonstrate lower functional connectivity and neuronal synchronization in individuals with RD as measured using coherence and ASSR (Lizarazu et al., 2021b; Mandke et al., 2022). These results suggest impaired neural tracking at theta in RD. In addition, greater neural entrainment was related to better reading and phonological processing (Abrams et al., 2009). Conversely, ASSR (using source reconstruction) and ITC were atypically enhanced in individuals with RD compared to TD individuals (Granados Barbero et al., 2021; Halliday et al., 2014; Lizarazu et al., 2015). Individuals with RD may rely more on the temporal sampling information related to the syllabic-rate. This neuronal compensation may be due to the lower functional connectivity and lack of hemispheric specialization in those with RD. The finding that there is lower theta entrainment in RD aligns with the TSF. However, not all the findings fit neatly into this theory, including the non-significant findings and atypical enhancement of neural entrainment in certain studies. The observed variability in these studies highlights the need for more comprehensive research of neural entrainment at theta in RD.

2.4.1.3 Alpha Band

A limited number of studies looked at neural entrainment in the alpha band, with several studies not finding significant differences between groups (Hämäläinen et al., 2012; Han et al., 2012; Keshavarzi et al., 2022; Lizarazu et al., 2021b; Zhang et al., 2022). The alpha band has been related to processing upper-syllable rates for which there is some evidence of less neuronal synchronization in individuals with RD (De Vos et al., 2017a; Granados Barbero et al., 2021; Van Hirtum et al., 2020). There is also a link between alpha and phonological awareness abilities (De Vos et al., 2017a). However, much of the research in this band demonstrates no significant differences between groups.

2.4.1.4 Beta Band

There was a variety of results at beta which was likely due to the diversity of methodologies used across studies. A few studies did not find significant differences between groups (Hämäläinen et al., 2012; Lizarazu et al., 2021b; Zhang et al., 2022) and the others found differences which varied based on the methodologies used (RD > TD for monaural stimulation; De Vos et al., 2017a; RD > TD for ASSR and connectivity for right-ear stimulation; Granados Barbero et al., 2021a; TD > RD for 30 ms rise times only; Van Hirtum et al., 2019). Results also varied by hemisphere and age (Chang et al., 2021; De Vos et al., 2017b; Dushanova et al., 2020; Granados Barbero et al., 2022; Lizarazu et al., 2015; Mandke et al., 2022; Poelmans et al., 2012). The focus of TSF is not the beta frequency band, but Goswami (2019) recently hypothesized that lower beta entrainment is related to worse onset-rime processing. The RAP theory more generally focuses on faster rates of processing. Neither framework really explains the variability in results at beta. However, the correlational results do have some relevance to the frameworks, which suggest that precise temporal processing is critical for language and reading development. Greater beta entrainment was found to be related to better literacy skills in adults with RD (Van Hirtum et al., 2019), as well as phonological awareness (De Vos et al., 2017a; Poelmans et al., 2012). A developmental increase in response amplitude was also associated with worse phonological and reading skills (De Vos et al., 2017b), suggesting that children with RD have an inefficient increase in neuronal activity at beta.

2.4.1.5 Gamma Band

There was also a variety of findings in this band, which depended on the specific frequency range and hemisphere. Four studies did not find any significant differences between RD and TD at low gamma (30-45 Hz; De Vos et al., 2017a; Han et al., 2012) and upper gamma (60 and 80 Hz; Lizarazu et al., 2015; Poelmans et al., 2012). However, five studies found that individuals with RD undersampled the acoustic information (weaker overall entrainment; De Vos et al., 2020; Lehongre et al., 2013; Lizarazu et al., 2021b; Rufener & Zaehle, 2021; Van Hirtum et al., 2019). One study found that individuals with RD oversampled the acoustic phonemic information (greater than normal neural entrainment; Granados Barbero et al., 2021). Two studies found mixed results depending on the frequency range and hemisphere (Dushanova et al., 2020; Lehongre et al., 2011), generally showing lower LH activity. The weaker overall neural entrainment and lower LH activity in RD is concordant with the TSF, RAP, and AST theories.

Giraud and Poeppel (2012) suggest a framework that explains why the brain may be oversampling and undersampling phonemic information, which can be considered a result of impaired auditory processing. Their framework proposes that the lower LH activity in individuals with RD may be due to the incorrect processing of phonemic units. To compensate for this, the RH oversamples acoustic details making it challenging to efficiently integrate speech information, which also negatively affects short-term memory. The incorrect processing of phonological information selectively impacts acoustic processing and memory. Indeed, individuals with RD exhibited reduced gamma entrainment, which was associated with poorer phonological awareness and reading fluency (Lehongre et al., 2011; Rufener & Zaehle, 2021). Conversely, TD individuals showed increased LH activity, correlating with greater reading fluency and phonological processing, while greater RH activity in those with RD was related to lower RAN (Lehongre et al., 2011). Furthermore, greater neural entrainment in individuals with RD was related to lower verbal working memory scores. Altogether, these findings indicate that individuals with RD inefficiently track the temporally relevant information in the speech signal. Further research looking at this phenomenon is needed to fully understand the mechanisms behind speech processing at gamma in RD.

2.4.2 Neural Entrainment DLD

The two studies looking at neural entrainment in children with DLD focused on the beta/gamma range (20-80 Hz). Children with DLD were found to have weaker neural entrainment to rapidly changing rhythmic information compared to TD children (Heim et al., 2011, 2013). These findings are in line with the RAP theory (Tallal & Piercy, 1973) positing that children with DLD have difficulties processing rapid temporal changes in auditory information. There were also promising gains in neuronal activity and oral language measures after the use of a language intervention program focused on RAP skills (Heim et al., 2013). The results demonstrate that children with DLD exhibit atypical neural entrainment which could explain deficits in encoding and processing acoustic information. However, improvements in language skills can be achieved using intervention programs.

2.4.3 Lateralization Effects

In line with the TSF (Goswami et al., 2011) and the Auditory Sampling Theory (AST; Poeppel, 2003), individuals with RD exhibited less RH lateralization at delta and theta frequency bands (Destoky et al., 2022; Di Liberto et al., 2018; Hämäläinen et al., 2012; Lehongre et al., 2013; Lizarazu et al., 2015, 2021b; Mandke et al., 2022; Molinaro et al., 2016). Greater RH lateralization at delta and theta were related to better reading and phonological processing (Abrams et al., 2009; Lizarazu et al., 2015). Moreover, at delta, the right auditory cortex was directly related to low coherence in the left inferior frontal gyrus (IFG), leading to lower overall neural entrainment (Dushanova et al., 2020; Molinaro et al., 2016). Further, RH specialization at delta was related to better language skills (Di Liberto et al., 2018; Molinaro et al., 2016), and RH specialization at theta was related to better RAN abilities (Destoky et al., 2022). For delta, greater neural entrainment in the LH was also found to be important for reading accuracy (Lizarazu et al., 2021a) and sight-word reading in individuals with RD (Molinaro et al., 2016), indicating that LH activity may also be important for reading efficiency. These findings demonstrate that individuals with RD have less specialized brain network organization, which could impact speech tracking and phonological processing.

For beta and gamma, the AST states that neuronal activity is typically left lateralized at higher processing rates (Poeppel, 2003). However, in beta, only one study found that TD individuals had greater LH activation compared to individuals with RD (Poelmans et al., 2012), with several studies finding differences between groups in the RH (Chang et al., 2021; Dushanova et al., 2020; Granados Barbero et al., 2021; Lizarazu et al., 2015). A few studies found that there was oversampling in the RH in individuals with RD. This is suggested to be a compensatory mechanism due to the lack of LH specialization in comparison to TD individuals. LH specialization is important for successful reading acquisition as it has been related to better phonological awareness and phoneme repetition performance (Lizarazu et al., 2015; Poelmans et al., 2012). The results for gamma; however, are in line with the AST, wherein TD adults had greater neural entrainment in the LH (Dushanova et al., 2020; Lehongre et al., 2011, 2013; Lizarazu et 2021b), which was related to better reading fluency, RAN, and phonological processing (Lehongre et al., 2011). Similar to beta, oversampling was also occurring in the RH in individuals with RD (Dushanova et al., 2020; Lizarazu et al., 2015), which is hypothesized to be due to compensation for the lack of LH specialization (Giraud & Poeppel, 2012), which is consistent with the idea that individuals with RD engage compensatory pathways to cope with reading difficulties (Horowitz-Kraus et al., 2014).

2.4.4 Developmental Effects

We also summarize differences in neural entrainment between groups as a function of age. A handful of studies looked at developmental differences longitudinally in theta, beta, and gamma (De Vos et al., 2017b, 2020; Granados Barbero et al., 2022). At theta, neural entrainment and connectivity were greater in TD 5- and 9-year-olds, but not 7-year-olds. Children with RD had greater neural connectivity at the age of 7 than TD children, which may be due to RD children exerting greater neural effort when receiving intensive reading training around 7 years (Granados Barbero et al., 2022). At beta, results from the longitudinal studies differed based on the methodologies used. ASSR was found to increase with age from 7- to 9-years-old in children with RD. This increase was related to worse reading, phonological awareness, and RAN (De Vos et al., 2017b). Using source activity reconstruction to measure ASSR on the same participants led to the opposite pattern of less ASSR with age, showcasing that neural entrainment results can drastically change based on the analysis methods used (Granados Barbero et al, 2022). Neural connectivity was also found to increase with age in children with RD, following the same pattern as the ASSR measure from De Vos et al. (2017b). Upper gamma (80 Hz) was found to remain stable after the start of reading instruction, when there was an atypical increase in 80 Hz ASSRs (De Vos et al., 2020), indicating that atypical neural entrainment at this frequency remains stable after reading development. There were also different patterns of laterality based on age. Granados Barbero et al. (2022) found RH lateralization in 5- and 7-year-olds, and not 9-year-olds with RD. This could indicate a late maturation of beta since symmetric neural entrainment has been observed in TD adolescents and adults (De Vos et al., 2017a; Granados Barbero et al., 2021a; Van Hirtum et al., 2019). These studies provide some insight into the maturational effects of neural entrainment; however, more studies are needed to better understand these developmental patterns.

2.4.5 Considerations for Future Research

The results of this review reveal the wide range of factors to consider when studying neural entrainment in children with language or reading disabilities. For instance, studies varied widely based on the specific frequency or frequency range chosen, which might have led to different results. For instance, in the beta band, Poelmans et al. (2012), Chang et al. (2021), and Mandke et al. (2022) focused on different frequency ranges and had different electrode selections, which resulted in different findings in terms of laterality. In many cases, beta overlapped with either alpha or gamma (e.g., Chang et al., 2021; Dushanova et al., 2020; Mandke et al., 2022; Poelmans et al., 2012) which led to different patterns of results. More work is needed to determine the optimal frequency ranges related to each language component in order to better focus analyses and improve reproducibility.

There were also variations in findings based on methodological decisions. Even though Granados Barbero et al. (2021a, 2022) used the same participants or a subset of participants from De Vos et al. (2017a, 2017b), the results greatly differed based on the way the ASSRs were extracted. Granados Barbero et al. (2021a, 2022) used source activity reconstruction which provides components with the most phase-locked activity while De Vos et al. (2017a, 2017b) did not. Results also varied based on which ear was stimulated (Granados Barbero et al., 2021), and the stimuli used. For instance, continuous speech yielded differences between groups (Mandke et al., 2022) but trisyllabic words did not (Zhang et al., 2022). Studies using stimuli with temporally regular acoustic cues, such as to amplitude-modulated white noise, and isochronous tones, syllables, and words (e.g., Doelling et al., 2014; Rufener & Zaehle, 2021), can inform us about entrainment at specific stimulus presentation frequencies. The use of controlled stimuli is valuable as it provides foundational information about neural entrainment mechanisms related to speech and paves the way for future research. Naturalistic speech, on the other hand, can provide more informative information relevant to real-world speech tracking.

Approximately 30% of studies used connected speech, which indicates an improvement in the ecological validity and the real-world implications of the research. Methods that target impaired neural entrainment can be developed based on findings of natural speech tracking to improve children’s phonological processing skills, and thus language and reading abilities. For instance, music-based interventions are easy and cost-effective strategies that can be used to help improve neural entrainment. Music rhythm training can help individuals with RD and DLD by training them on relevant time points, which could improve prosody, syllable processing, phonological processing, reading, and auditory perception (Fiveash et al., 2021; Habib et al., 2016).

Since results can change methods based on the methodologies used, we recommend preregistering the methods to increase reproducibility, transparency, and reduce reporting bias. One such issue is that researchers may explore a variety of approaches, but only report the ones with favourable outcomes, potentially inflating Type I error (Simmons et al., 2011). For instance, variability in results may occur when selecting frequency bands or electrode combinations which show a more favourable effect. Another concern is the file drawer effect, in which only studies with favourable results get published. In the context of our review, this may mean that we have not fully captured cases where individuals with RD and DLD did not have impaired/atypical neural entrainment. The only way to overcome these issues is through reproducible, open science where we pre-register analyses and agree upon standard analytic methods. If we adopt these practices, this could lead to the combination of datasets, thereby increasing statistical power and allowing for more robust insights into complex topics.

2.4.6 Gaps and Limitations

Because of the large variability across studies, conducting meta-analyses was not possible. A meta-analysis combines the effect sizes from each study to come to stronger conclusions about the research question (Borenstein et al., 2009). We could have conducted meta-analyses on the few studies that had enough commonalities; however, the risk of having an unreliable estimate of the effect and confidence intervals outweighed the benefits of conducting meta-analyses (Borenstein et al., 2009). This is still a new area of research but with more replication studies and studies using similar methodologies, meta-analyses can then be conducted.

Another gap that we identified is that there are fewer studies looking at neural entrainment in individuals with DLD. In most regards, DLD is an understudied population; however, it is just as prevalent as RD and is also highly comorbid with RD and other disorders (e.g., ADHD, motor, or speech problems; Bishop et al., 2017; McGregor, 2020). The DLD studies in this review were also focused on the beta-gamma frequency range, which limits our knowledge on the overall role of neural entrainment in language disorders. To fully understand how neural entrainment affects language processing, it is especially important to study this population since this disorder is directly related to learning, understanding, and using language. With more studies focusing on this population, more direct comparisons of neural entrainment across frequency bands can be made between RD and DLD. This would allow for a better understanding of where differences and similarities in neural processing exist across disorders and sub-categories of the disorders (i.e., DLD presents in multiple forms with some presenting with impairments in e.g., syntax, and pragmatic language; Bishop et al., 2017).

Although we identified several studies looking at brain-behaviour correlations between neural entrainment and language and reading measures, these generally focused on the delta and theta bands with the fewest in the beta band. Further, no brain-behaviour correlations were conducted on the studies that looked at children with DLD. Addressing these gaps in future research can provide valuable information about the connections between impaired neural entrainment and language and reading abilities across each frequency band.

A limitation of this review is that we only included articles and searched databases of papers written in English. We excluded non-English articles and databases due to limited access to non-English databases and reviewers' limited understanding of other languages. This could introduce English language bias; however, the included studies do report on several languages, which add to the body of knowledge. Further, none of our searches found non-English articles; although this may reflect the search databases chosen, it does suggest that the existing literature on the topic is published in English.

2.4.7 Conclusions

This systematic review details the state of the literature on neural entrainment in individuals with reading and language disorders. While some studies demonstrate impaired neural entrainment and atypical lateralization in individuals with RD and DLD, especially in the delta, theta and gamma bands, findings are inconsistent across studies, possibly due to differences in methodologies. Taking a step back to compare and standardize methodologies may provide these answers. Importantly, the large number of studies examining entrainment in reading disability, highlights a clear lack of congruent studies in individuals with DLD. Future studies focusing on this population would help elucidate other potential areas of impairment in neural entrainment and would then allow for a more direct comparison between RD and DLD. Importantly, the link between entrainment and models of reading and language disability suggest that this line of research has a long-term promise of informing interventions in affected individuals.

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Articles with asterisks indicate the articles included in the systematic review.

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Chapter 3

3 Neural Entrainment of Natural Language in a Large-Scale Sample of School-Aged Children

3.1 Introduction

Our brains have the exceptional ability to align neuronal oscillations to external rhythmic input, known as neural entrainment. This phenomenon plays an important role in auditory (Cabral-Calderin & Henry, 2022; Obleser & Kayser, 2019), visual (Bauer et al., 2021; Köster et al., 2019), and speech perception (Ahissar et al., 2001; Peelle & Davis, 2012), and is related to cognitive processes, such as attention (Calderone et al., 2014) and learning (Michael et al., 2023). Crucially, neural entrainment to rhythmic auditory stimuli has been shown to be important for speech processing (Poeppel, 2014), and has been causally related to improved speech processing (Keshavarzi & Reichenbach, 2020; Riecke et al., 2018; Zoefel et al., 2017). Neural entrainment to speech features, such as prosody, phonemes, syllables, and words, have been clearly shown in infants (Cantiani et al., 2022; Choi et al., 2020), children, and adults (Batterink & Paller, 2017; Moreau et al., 2022; Vanden Bosch der Nederlanden et al., 2020), and can occur at varying timescales (Giraud & Poeppel, 2012).

Specific frequency bands have been shown to correspond to distinct speech features. Much research has focused on the delta band (< 4 Hz), which involves the slowest oscillations and has been related to processing prosodic information such as stress and intonation (Ding & Simon, 2014; Giraud & Poeppel, 2012). This band is also hypothesized to be foundational for the hierarchical organization of the incoming speech signal, crucial for the extraction of complex linguistic information (Giraud & Poeppel, 2012). For instance, delta rhythms help with the extraction of phonemic units, which contributes to speech comprehension. Theta oscillations (4-8 Hz) are also considered slow-wave oscillations and are important for speech perception as they entrain to syllable onsets, which helps with syllable segmentation and identification (Howard & Poeppel, 2012; Luo & Poeppel, 2007; Meyer, 2018). Alpha (8-12 Hz) has also been related to processing phonemic information (Keitel et al., 2018; Vanden Bosch der Nederlanden et al., 2022), and to verbal working memory (Chen et al., 2023; Meyer, 2018). Beta and gamma (> 25 Hz) are fast wave oscillations that have both been related to processing phonemic information (Giraud & Poeppel, 2012; Meyer, 2018). Beta is hypothesized to help with the integration of phonemic information during speech perception and with lexical-semantic predictions, while gamma is thought to be especially important for processing rapid acoustic changes related to phonemic segmentation, binding, and the processing of fine structure information (Meyer, 2018; Di Liberto et al., 2015; Lewis et al., 2016). Stronger neural entrainment to these speech features is related to better phonological processing, speech perception, and reading comprehension (Abrams et al., 2009; Doelling et al., 2014; Colling et al., 2017). Since each frequency band is related to specific features in speech, it is important to assess neural entrainment at multiple levels.

Neural entrainment can be measured using electroencephalography (EEG) or magnetoencephalography (MEG), which capture millisecond-level fluctuations in neuronal activity (Luck, 2014). There are a variety of ways in which neural entrainment can be measured. For instance, phase-locking measures can tell us how strongly aligned the brain’s oscillations are to rhythmic stimuli. Among these, inter-trial phase coherence tells us how strongly oscillations are phase-locked across trials, with high values indicating strong and consistent phase entrainment (Tallon-Baudry et al., 1996). Cross-correlation also tells us how strongly two signals are aligned, specifically in the time domain (Abrams et al., 2009). A promising measure is cerebro-acoustic phase coherence (CAPC). It directly assesses the alignment of the phase of the neural oscillations to the amplitude envelope of the auditory stimuli. CAPC is especially well-suited for assessing the relationship between neural oscillations and continuous auditory stimuli because it is sensitive to the temporal dynamics of the signal. It also provides clear interpretations of the strength of the relationship at specific frequencies and frequency bands (Peelle et al., 2013; Vanden Bosch der Nederlanden et al., 2020). Past studies have found robust CAPC to continuous speech at low delta and theta (Bourguignon et al., 2013; Peelle et al., 2013) demonstrating its utility at quantifying neural entrainment to complex auditory stimuli.

Another important avenue of research investigates neural entrainment in individuals with reading disability (RD; e.g., Lehongre et al., 2013), and developmental language disorder (DLD; e.g., Heim et al., 2013). Investigations into these individuals demonstrate atypical and/or weaker neural entrainment (see Chapter 2). These disorders are believed to stem from deficits in rhythmic auditory processing, specifically in synchronizing neural oscillations (Cumming et al., 2015; Goswami, 2011). The disruption of regular neural entrainment is hypothesized to lead to difficulties in processing fast acoustic changes in speech, which may affect phonological processing, speech segmentation, and orthographic mapping. Studying neural entrainment in populations with varying language and reading abilities is especially informative as it can provide insights into how different brains process rhythmic information and how it is related to behavioural performance on language, reading, and phonological processing tasks. Looking at populations beyond the typically developing will contribute to our broader understanding of how humans learn and process language.

3.1.1 Current Study

The current study aims to expand on previous findings by measuring CAPC in children with a spectrum of language and reading abilities. This is to increase the generalizability of research findings to all children as we are not excluding based solely on diagnostic criteria. We used the Child Mind Institute Healthy Brain Network database (HBN). The HBN is an ongoing large-scale initiative based in New York that has the goal of creating and sharing data from 10,000 participants between the ages of 5 and 21. We analyzed EEG recordings in a large group of children watching and listening to a three-minute-long video and investigated whether we could measure CAPC (i.e., phase alignment of the neural oscillations to the amplitude envelope of the speech signal). In addition, we correlated language and reading measures with CAPC to determine whether there was a relationship between the strength of neural entrainment and behavioural performance. With this research, we will be able to determine whether CAPC is an appropriate measure for assessing neural entrainment in a large group with limited data. This research will also allow us to assess the link between neural entrainment and language and reading abilities in children.

3.2 Methods

Full details of the HBN dataset are described in Alexander et al. (2017). Data from this study included basic demographic information, behavioural and cognitive information, as well as EEG data from children listening and viewing a short video.

3.2.1 Participant Selection

A total of 712 children between 5-18 years (*M* = 10.17 years, *SD* = 3.33 years; 270 females, 442 males) from releases 1-9 were included in the study. Children under 19 years old with complete datasets (i.e., all demographic, behavioural and EEG data) were required for the present study (*n* = 1665). Children were excluded if they had an incomplete diagnostic evaluation or had a diagnosis of autism spectrum disorder (*n* removed = 285); missing EEG data for the video of interest titled “Fun with Fractals” (*n* removed = 119); if preprocessed EEG data was not available (*n* removed = 537); or did not view at least half of the video (*n* removed = 7). Five other participants were excluded due to other errors (i.e., wrong event codes, wrong sampling rate, deleted from release, unable to download).

3.2.2 Tasks

The following tasks were used to assess children’s language and reading abilities. To make diagnoses of developmental disabilities, tests were administered and scored by clinicians. Further, the responses were scored again by a research assistant and double entered by two other research assistants to ensure validity of the responses. Children were administered a battery of assessments, including behavioural and cognitive testing, by a clinician to make official diagnoses, such as the Schedule for Affective Disorders and Schizophrenia—Children’s version (KSADS; Kaufman et al., 1997). Children suspected of having a language disorder, based on the Comprehensive Evaluation of Language Fundamentals (CELF-5) Screener (Semel et al., 1995), were given a battery of language tasks assessing oral language skills, expressive and receptive vocabulary, and articulatory skills (see Alexander et al., 2017 for more details).

The standard scores from the language and reading assessments were used to determine the relationship between CAPC and language and reading scores. The CELF-5 screener was used since all participants were administered this measure. The elision, blending subtests, and the composite rapid symbol naming scores from the Comprehensive Test of Phonological Processing (CTOPP-2; Wagner et al., 2013) were used, which assesses phonological processing abilities. The Test of Word Reading Efficiency (TOWRE-2; Torgesen et al., 2012) scores were also used for correlations. This task is timed and measures participants’ fluency and speed when pronouncing printed words (Sight Word Efficiency, SWE) and non-words (Phonemic Decoding Efficiency, PDE). Finally, the Weschler Individual Achievement Test (WIAT III; Weschler, 2009) provides information on general achievement skills. The composite measure, listening comprehension and oral discourse, was used for correlations. We also conducted correlations with the Expressive Vocabulary Test (EVT-2; Williams, 2007) and Peabody Picture Vocabulary Test (PPVT; Dunn & Dunn, 2007). These tasks were only conducted on individuals who were suspected of having a language disorder therefore the correlations were only conducted on this subset of children.

3.2.3 EEG Procedures

The EEG session was approximately 75-90 minutes long. For the naturalistic viewing paradigm, participants viewed four short video clips that were age appropriate, “Despicable Me”, “Diary of a Wimpy Kid Trailer”, “Fun with Fractals”, and “The

Present”. The first three videos were played in random order, with “The Present” always being played last. The full EEG procedure is described in Langer et al. (2017).

3.2.4 Stimuli

The video clip used in this study is “Fun with Fractals”, a 2.72-minute-long educational video clip, voiced by a female speaker (found at https://wwwyoutubecom/watchv=XwWyTts06tU). This clip describes fractal-based geometry with still images to depict how some fractals are created. This video was chosen over the other videos because it contained the greatest amount of phonation time (i.e., total amount of speaking time) and it contained very little distracting video information, such as action scenes or written text. Because this video was not dynamic, the temporal dynamics of the video were less likely to contaminate our measure of CAPC.

The clip information is summarized in Table 3.1. Acoustic-phonetic information was calculated using the Praat Speech Rate script developed by de Jong and Wempe (2009).

Table 3.1. Full Fun with Fractals clip information.

No. of syllables	No. of pauses	Duration (s)	Phonation time (s)	Speech rate[1]	Articulation rate[2]	Syllable Duration[3] (ms)
685	37	163	139.48	4.2	4.91	204

Notes. [1] syllables per second. [2] syllables divided by phonation time (s). [3]phonation time divided by the number of syllables.

3.2.5 EEG Recording and Preprocessing

EEG data were recorded using a 128-channel EEG Geodesic Hydrocel system at a sampling rate of 500 Hz, bandpass filtered 0.1 to 100 Hz, referenced to vertex. Electrode impedance was kept below 40 kOhm and was re-evaluated every 30 minutes with saline added if necessary. All preprocessing steps were conducted by Langer et al. (2017), as follows. There were 109 scalp electrodes, 9 EOG electrodes (forehead, outer and inner canthi), and the remaining electrodes on the chin and neck. The outermost electrodes (chin and neck) were excluded for a total of 111 channels. If a channel had a variance more than 3 SD from the mean, these were identified as bad channels, and interpolated using spherical spline interpolation (Perrin et al., 1987; 1989). Noisy channels were visually inspected and interpolated or replaced by zeros. The EEG data were high-pass filtered at 0.1 Hz and notch filtered at 59–61 Hz with a Hamming windowed-sinc finite impulse response zero-phase filter with an order of 25% of the lower passband edge. Eye artifacts were removed by linearly regressing the EOG channels from the scalp EEG channels. A Principal Components Analysis (PCA) algorithm (Lin et al., 2010) was then used to remove sparse noise from the data. Lastly, the entire dataset was visually inspected and if whole blocks and/or whole recordings remained noisy, they were discarded.

Following this, the first 3552 ms were removed of the EEG data and audio since there was no speech, only music, in the video. We segmented the data into 39 nonoverlapping 4000 ms epochs. There was a 40th epoch of 3000 ms, which was removed from analyses since it was not the full length of the other 39 epochs. The 159 second video was similarly divided into 4000 ms audio segments aligned to the EEG segments.

3.2.6 Cerebro-Acoustic Phase Coherence

CAPC was calculated as in Vanden Bosch der Nederlanden et al. (2020): the amplitude envelope of the video clip’s audio was extracted by separating the frequency spectrum into 10 bands of equal width. This was done using Liberman’s (1982) cochlear frequency map from 180 to 22,000 Hz to approximate the human auditory system. To extract the amplitude envelopes, the Hilbert transform was used. The envelope from each band was then low-pass filtered at 100 Hz and high-pass filtered at 0.1 Hz. The mean of the filtered envelopes was multiplied by a tapered Hamming Window and an energy correction of 1.633. This was to equate the original signal amplitude to the RMS amplitude. The Fourier transform for each epoch was then halved. The audio segments were downsampled to 500 Hz to match the EEG sample rate.

FieldTrip’s (Oostenveld et al., 2011) *ft_freqanalysis* was used to transform EEG data to the frequency domain. The Fourier transform *mtmfft* was used to obtain the cross-spectral density of the EEG and amplitude envelopes and ± 1 Hz taper smoothing frequency. Second, FieldTrip’s *ft_connectivityanalysis* was used to calculate the phase alignment between the EEG and the acoustic amplitude envelopes. This yielded a measure of coherence from 0 (no phase alignment) to 1 (complete phase alignment). Fronto-central electrodes (see Figure 3.1) were chosen for the analyses following prior work suggesting CAPC effects tend to be maximal in this scalp region (e.g., Vanden Bosch der Nederlanden, 2020).

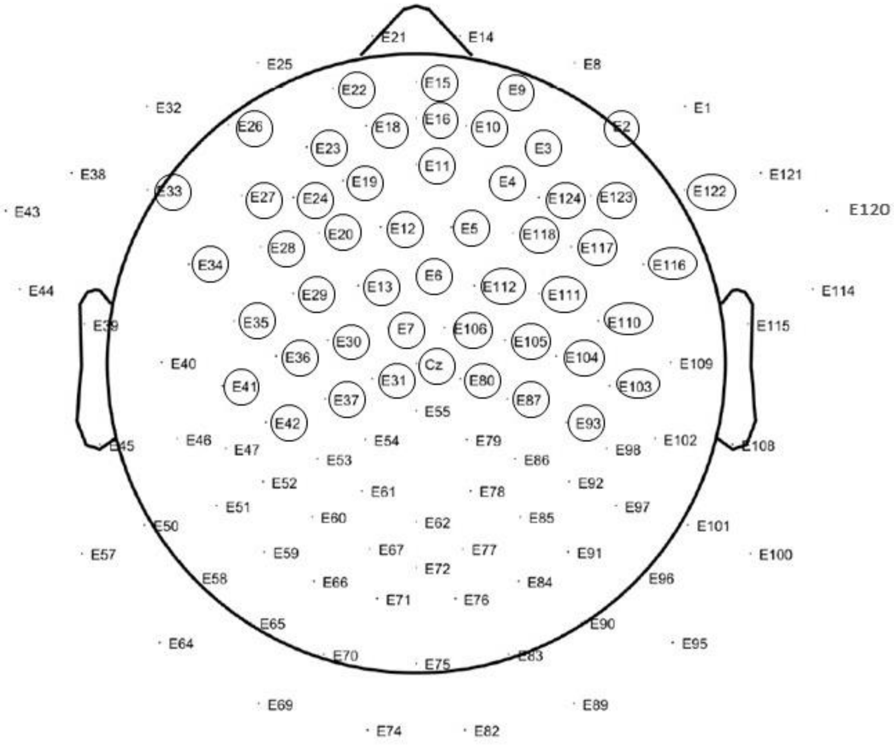

Figure 3.1. Selected electrodes used in the analyses.

3.2.7 CAPC across Children

For statistical analyses, CAPC was calculated for each fronto-central electrode and then averaged at each frequency band across all electrodes. For each participant, coherence was also calculated for 100 random permutations of EEG and stimulus epochs. Coherence values were then z-score transformed from 0.5–40 Hz by subtracting true coherence values by the randomly permutated coherence values and dividing with the standard deviation of the randomly permutated coherence values. The z-score transformed coherence values were compared to chance using a two-tailed one-sample t-test corrected for the False Discovery Rate (FDR) across the selected frequencies. Correlations were then conducted between the language and reading measures and the z-score coherence values for all fronto-central electrodes. These correlations were also FDR corrected.

3.2.8 Cross-Group Analyses

We also compared coherence values across groups. We looked at whether there were any differences between typically developing children (TD, *n* = 153), children who were diagnosed with a specific impairment in reading (reading disability; RD; *n* = 72), and children who were diagnosed with a language disorder (also called developmental language disorder; DLD; *n* = 65) using a MANOVA at each frequency band of interest.

3.3 Results

3.3.1 CAPC across Children

The one-sample t-test after FDR correction demonstrated significant coherence values above zero for low theta at 3.25-5 Hz (see Figure 3.2). Correlations between coherence and the behavioural measures were thus only conducted on this range.

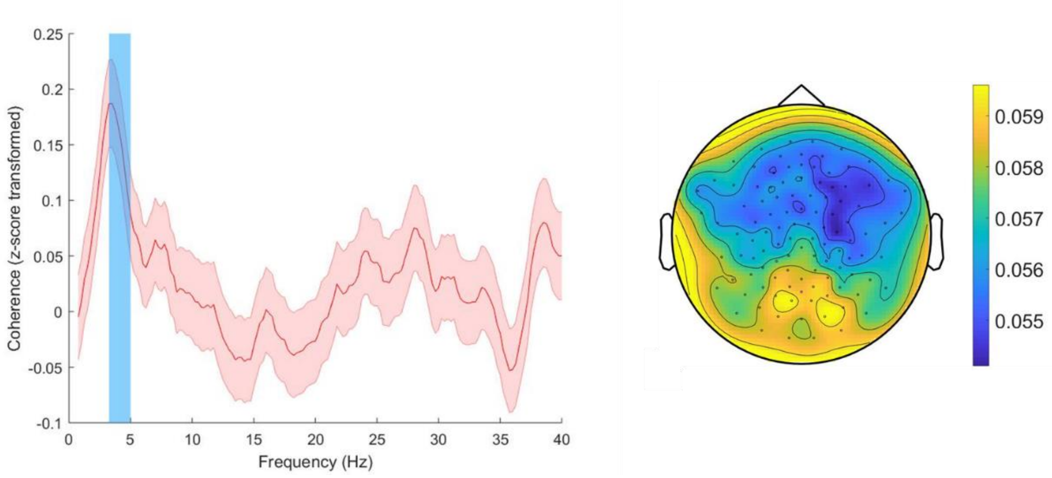

Figure 3.2. Z-score transformed CAPC of the average of the selected electrodes from 0-40 Hz (on the left). The blue box indicates where the values were significantly above zero after FDR correction. The topographical plot (on the right) demonstrates the CAPC within that range (3.25-5 Hz).

3.3.2 Correlations

We examined how language, reading and cognitive achievement measures correlated with low theta. There were no significant correlations after FDR correction (see **Error! Reference source not found.**).

Table 3.2. Correlations between behavioural measures and CAPC for low theta. Significance and FDR corrected significance included.

Behavioural measures	*r*	*p*	p_{FDR}
FSIQ	-.008	.841	.934
CELF	-.01	.727	.934
CTOPP Blending	.02	.645	.934
CTOPP Elision	.009	.830	.934
CTOPP RSN	-.05	.225	.564
TOWRE PDE	-.06	.128	.564
TOWRE SWE	-.04	.336	.671
WIAT LCODC	-.002	.967	.967
EVT	-.29	.020	.201
PPVT	-.17	.181	.564

3.3.3 Group Comparisons

There were no significant differences between groups in the average frequency ranges (Delta: *F*(2, 283) = .34, *p* = .851; Theta: *F*(2, 283) = .46, *p* = .768, Alpha: *F*(2, 283) = .72, *p* = .581; Beta: *F*(2, 283) = .30, *p* = .878, Gamma: *F*(2, 283) = 1.76, *p* = .132). Figure 3.3 compares coherence for each group across 0-40 Hz.

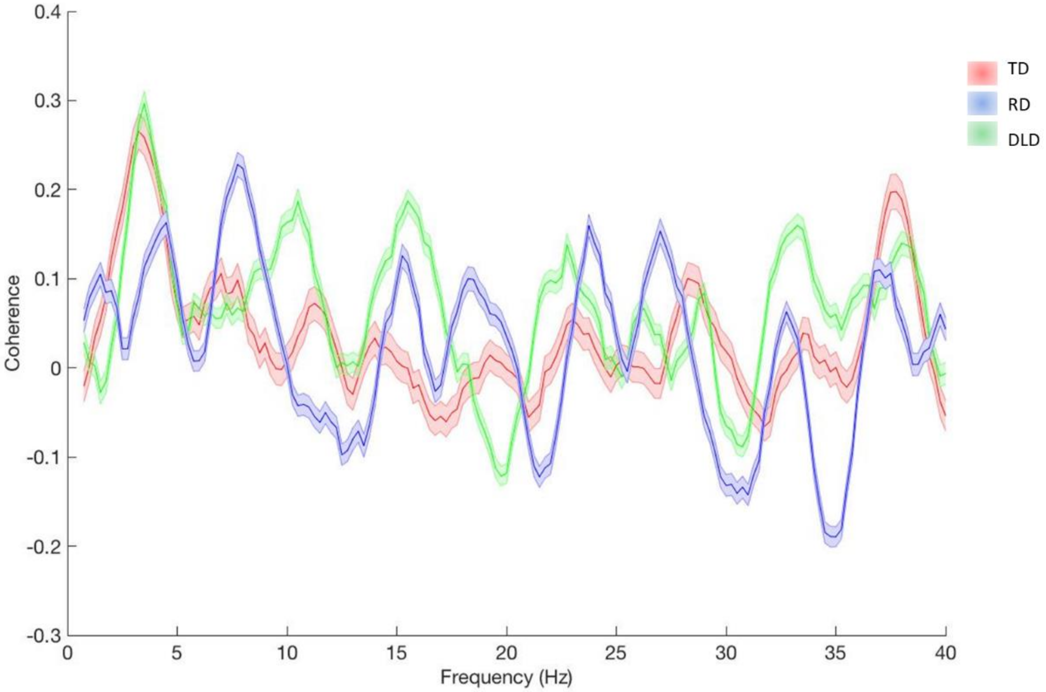

Figure 3.3. Z-score transformed CAPC of the average of the selected electrodes from 0-40 Hz for TD (red), RD (blue), and DLD (green).

3.4 Discussion

In this study, we looked at cerebro-acoustic phase coherence (CAPC) in children aged 5-18 years using a large database, but with a limited amount of data per child. Specifically, we had a little over two minutes of speech data with which to measure neural entrainment in children. Our sample included children who were typically developing (TD), had developmental language disorder (DLD), reading disability (RD), and children who had other disorders (e.g., attention deficit hyperactivity disorder). This was done so that we could look at CAPC based on the range of language and reading scores, increasing the generalizability of the findings. We also conducted additional analyses on TD, DLD, and RD children to determine whether there were differences in CAPC based on groupings of official diagnoses of language and reading disorders.

3.4.1 CAPC across Children

First, we looked at whether there was significant CAPC in all children, and we found significant neural entrainment at 3.25-5 Hz. This closely corresponds to the lower limit of the theta frequency band, which is related to syllabic processing. Syllables tend to occur at a rate of 3–7 Hz in normal speech (Ghitza, 2011; Poeppel et al., 2008). Further, Ding et al. (2017) examined a large corpus of auditory recordings in nine languages and found a peak in the spectrum between 4 and 5 Hz across languages. These findings indicate that we were able to find significant CAPC for syllabic processing even after short exposure to speech information. Importantly, this is one of the first studies to find significant neural entrainment to naturalistic speech in such a short recording. However, previous studies using natural speech have found neural entrainment at other important frequency bands, including the delta, alpha, and gamma bands (e.g., Ding et al., 2017; Gross et al., 2013; Keitel et al., 2018; Vanden Bosch der Nederlanden, 2020). It is possible that we only found entrainment in a narrow frequency range because of our limited amount of data, which would limit power. The studies that found neural entrainment in other frequency bands had longer exposure periods and some studies also repeated the same sentences, which led to greater overall power. It is important to note that we measured CAPC similarly to Vanden Bosch der Nederlanden et al. (2020), who also did not find significant phase coherence at delta for their uncompressed speech condition. This could be a limitation of the method which may not be sensitive enough to detect neural entrainment at this lower frequency range. This may also depend on the stimulus itself as previous studies have suggested that theta is related to speech-specific processing whereas delta is more relevant for non-speech-specific rhythmic processing (Ding & Simon, 2014; Doelling et al., 2014). The children's neural oscillations may be entraining more to syllabic rather than rhythmic information. The most important takeaway from these findings is that CAPC is sensitive to syllabic information even with limited data.

3.4.2 Correlations

We conducted correlations between the language and reading measures with CAPC in all children. None of these correlations were significant after correcting for multiple comparisons. This is in line with other studies which have also not found significant correlations between reading and neural entrainment at delta and theta. For instance, Lizarazu et al. (2021) and Poelmans et al. (2012) did not find any significant correlations between their measures of neural entrainment (cross-correlation and ASSR) with reading, phonological skills, and rapid automatized naming. However, this does not necessarily mean that a relationship does not exist between neural entrainment and language and reading abilities. It is possible we were not able to find a significant relationship because our measure of coherence was not robust enough, meaning that it may not be the best measure of neural entrainment. Several studies have found that there is a relationship between language and reading with various measures of neural entrainment at delta and theta (e.g., Abrams et al., 2009; Colling et al., 2017; Di Liberto et al., 2018; Lizarazu et al., 2021a), as well as beyond these frequency bands (e.g., De Vos et al., 2017a; Lehongre et al., 2011). More research is needed to better understand these mixed findings and determine the direct relationship between neural entrainment and language and reading abilities.

3.4.3 Cross-Group Findings

We investigated whether there were differences in CAPC depending on whether individuals had official diagnoses of DLD or RD compared to TD. The Temporal Sampling Framework (TSF) posits that individuals with RD and DLD have weaker neural entrainment to speech at frequencies under 10 Hz (Goswami, 2011; Richards & Goswami, 2015). However, there were no significant differences in average CAPC between groups in any of the frequency bands. These findings suggest that these groups have similar CAPC irrespective of language and reading abilities. This idea is further supported by the non-significant relationships between language and reading scores with CAPC. There are also a number of studies that have demonstrated that there are no significant differences between RD and TD at theta (e.g., De Vos et al., 2017a, Fiveash et al., 2020; Keshavarzi et al., 2022; Molinaro et al., 2016; Power et al., 2013). These findings are not in line with the TSF, demonstrating that neural entrainment is not weaker in individuals with RD and DLD. However, other studies have found significant differences between groups at delta (e.g., Abrams et al., 2009; Di Liberto et al., 2018; Lizarazu et al., 2021a; Molinaro et al., 2016), and in upper frequency bands like gamma (e.g., Lehongre et al., 2011; Lizarazu et al., 2015). These findings demonstrate that individuals with RD have impairments processing acoustic information, which is in line with the TSF. Our inability to find differences between groups may be due to the specific frequency band where we found significant neural entrainment (3.25-5 Hz), which corresponds more to the theta frequency band. These findings demonstrate that syllabic processing is similar in individuals with and without language and reading impairments.

3.4.4 Limitations

The biggest limitation of this study is that we did not have specific timing for the YouTube video that was used during EEG recording. The timestamps for the video were given in seconds, with the millisecond information not supplied. Since CAPC depends on millisecond-level timing, aligning the amplitude envelope with the EEG signal, this could have impacted the strength of CAPC. In addition, other methods of neural entrainment may be more powerful at detecting entrainment. For instance, forward encoding models allow for the extraction and measurement of neural entrainment of specific speech features (e.g., phonemes, semantics; Crosse et al., 2016). These models have been demonstrated to be sensitive to shorter stimuli (e.g., Di Liberto & Lalor, 2017; Mesik & Wojtczak, 2023) and can be used to predict neural patterns to specific speech features based on diagnoses (e.g., Di Liberto et al., 2018).

3.4.5 Implications and Future Directions

Our findings demonstrate that neural entrainment can be measured with only a short exposure to speech stimuli. This is important for multiple reasons. Large-scale projects typically use shorter stimuli to lessen testing fatigue. This demonstrates that neural entrainment research is possible when using large databases with only short segments of data available. Even when in-person testing in children is not possible (such as during the Covid-19 pandemic), research questions can still be answered by using already existing neuroimaging data. These findings also demonstrate that neural entrainment can be measured in a very short amount of time which can be especially important for uncovering neural patterns to speech in children with diverse abilities.

This is the first study to investigate neural entrainment to short natural continuous speech using a larger dataset. Our findings provide further evidence that children with RD and DLD are not significantly impaired at tracking syllabic information compared to TD children. This information could help inform interventions targeting speech tracking in individuals with RD and DLD. These interventions, such as those focusing on rapid auditory processing (e.g., Heim et al., 2013) and rhythm-based interventions (e.g., Fiveash et al., 2021), can focus on targeting other aspects of speech that are impaired. For instance, transcranial alternating current stimulation (tACS) at 40 Hz (gamma) can be used to improve phoneme categorization in individuals with RD (Rufener et al., 2021).

3.4.6 Conclusions

This study investigated whether neural entrainment to a short clip can be measured using CAPC, which looked at the phase alignment of neural data to speech stimuli. We found significant neural entrainment at low theta, indicating alignment between EEG data and syllabic information. However, no significant correlations were found between CAPC and language and reading. In addition, no differences were found based on diagnoses of language and reading disorders. These findings are in line with previous findings indicating that children with RD and DLD have similar neural entrainment to syllabic information compared to TD children. Future studies should look at neural entrainment using measures that have been shown to be more robust with a limited amount of data. Our findings can be used to inform interventions targeting specific deficits in speech tracking.

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Chapter 4

4 A Multivariate Approach to Neural Entrainment in Children with Reading and Language Disorders

4.1 Introduction

Studies using electroencephalography (EEG), electrocorticography (ECoG) and magnetoencephalography (MEG) have established that neural entrainment to natural continuous speech occurs at multiple timescales (Ahissar et al., 2001; Ding et al., 2016; Nourski et al., 2009). Neural entrainment, the synchronization of brain oscillations to external stimuli, is particularly relevant when examining the amplitude envelope of continuous speech as it contains rich information such as prosody, phoneme boundaries, and word/phrase segments (Giraud & Poeppel, 2012; Luo & Poeppel, 2007; Myers et al., 2019). Neural entrainment occurs for each of these speech features. Notably, the lower frequency bands play a crucial role in processing prosodic, stress, phrasal, and syllabic information (Giraud & Poeppel, 2012; Goswami, 2011). Delta waves (< 4 Hz) are related to non-speech-specific rhythmic processing (e.g., prosody, stress), while theta waves (4-8 Hz) encode speech features important for speech intelligibility (e.g., syllables; Ding & Simon, 2014; Giraud & Poeppel, 2012; Keitel, 2018; Keshavarzi et al., 2020). There is also some evidence that alpha might play a role in verbal working memory (Meyer, 2018) as well as encoding upper syllabic and phonemic information (Edwards & Chang, 2013; Keitel et al., 2018). Our neural oscillations synchronize with multiple speech features, which is vital for successful language processing and comprehension.

There are multiple methods in which neural entrainment can be measured. One particularly useful approach is the multivariate Temporal Response Function (mTRF), which is designed for measuring complex temporal neural responses to multiple stimulus features from natural continuous speech (Crosse et al., 2016). There are two models that can be derived from this approach, a forward (or encoding) model and a backward (or decoding) model. Backward models reconstruct stimulus feature(s) from the neural response, and forward models map the stimulus feature(s) to the neural response. Speech features can be individually or collectively assessed to determine the mapping between each feature and the neural response. Backward models are useful because they use neural data from the whole head to optimize stimulus feature reconstruction, and projects to the stimulus domain which usually has access to the ground truth. However, the coefficients derived from this approach are not easily interpretable in terms of brain processes (Crosse et al., 2021; Haufe et al., 2014). Decoders are also more suited for analyzing continuous stimulus features (such as the spectrogram) and not discrete speech features (such as phonemes or semantic information). On the other hand, forward models can be fit using continuous and discrete features, and therefore can be used to identify which speech feature(s) drive neural activity. This approach relates speech features to neural responses over time and provides a straightforward way to measure neural entrainment to continuous speech. The TRF, which uses linear ridge regression for the stimulus-neural mapping, has certain advantages over other methods as it is less prone to temporal smearing, accounts for multicollinearity, and prevents model overfitting (Crosse et al., 2016).

Importantly, speech features can be differentiated temporally and spatially across electrodes (e.g., Broderick et al., 2018; Di Liberto et al., 2015; Di Liberto & Lalor, 2017). Each feature, including their spatiotemporal distinctions, can be modeled to determine their accuracy in predicting a left-out segment of data from each participant or by predicting a left-out participant's data (Di Liberto & Lalor, 2017). The resulting prediction correlation values (henceforth prediction values) quantify the degree of synchronization between neural patterns and each speech feature and can be used to look at neural differences between groups. Better EEG prediction values correspond to stronger phase-locking between the stimulus and neural signal (Di Liberto et al., 2018). Encoding models can provide more detailed information on neural entrainment than other methods because the degree of neural entrainment can be quantified for each speech feature. This would allow for better understanding of which speech features show atypical neural patterns in different populations.

Di Liberto et al. (2018) were the first to use forward encoding models to compare tracking of spectral-acoustic and phonetic features in children with reading disability (RD; also known as dyslexia) and typically developing (TD) children. Children with RD have been found to have difficulties in reading and phonological processing, including accurate and/or fluent word recognition, and decoding abilities (Hulme & Snowling, 2016). Phonological processing difficulties are hypothesized to be due to a temporal sampling deficit below 10 Hz (Temporal sampling framework (TSF); Goswami, 2011, 2018), related to poor tracking of rise time changes. These variations in rise time provide cues for syllable segmentation, such as syllable stress and phonetic distinctions. Low-frequency entrainment has also been found to directly reflect phonemic processing (Di Liberto et al., 2015). Indeed, Di Liberto et al. (2018) found impaired low-frequency cortical tracking to acoustic and phonetic information in RD, with the model demonstrating a different neural pattern than the TD groups. Phonological and reading measures were also correlated with the combined phonetic and acoustic models, further demonstrating the importance of neural entrainment in reading-related abilities. Similarly, Klimovich-Gray et al. (2023) investigated individuals with RD and found reduced envelope tracking in those with RD. Both studies found that this effect was mainly in the right hemisphere (RH), providing evidence for the Asymmetric Sampling in Time (AST) theory which states that typical language processing to slower oscillations primarily occur in the RH (Giraud & Poeppel, 2012).

Investigating other learning disorders can also provide insights into the importance of the role of neural entrainment in language processing and comprehension. One such disorder is developmental language disorder (DLD, previously Specific Language Impairment), which is equally as prevalent as RD (Bishop, 2010) and often co-occurs with it (Bishop & Snowling, 2004). DLD is characterized by a delay in oral language abilities, such as language production and comprehension, and may extend to difficulties with grammar, reading and spelling (Bishop et al., 2017). Much like RD, individuals with DLD are also proposed to have difficulties with phonological processing (Catts et al., 2005) which is once again hypothesized to be related to impairments in speech tracking (Richards & Goswami, 2015), and rapid auditory processing (RAP; Tallal & Piercy, 1973). The RAP theory hypothesizes that children with DLD (and to some extent RD; Boets et al., 2011), have deficits in processing and/or discriminating rapidly changing auditory information which may impair phonological processing. Indeed, relative to TD children, children with DLD exhibit weaker neural tracking to rapidly changing temporal information (Basu et al., 2010; Elmahawalli et al., 2021; Heim et al., 2011, 2013). However, studies have also found that individuals with DLD additionally present impaired speech tracking to slower aspects of speech presented via the amplitude envelope (Hämäläinen et al., 2012; Richards & Goswami, 2015). Previous EEG speech tracking studies in DLD have focused on upper frequency bands, relating findings to the RAP theory. However, little is known about the neural patterns related to speech tracking in the lower bands and how the findings relate to the TSF. Mapping acoustic and phonetic speech features to the neural response of individuals with DLD will provide insights into how this population tracks slower, but crucial, speech information. This would also inform us on how this population's neural activity differs from that of TD and RD children. Further, studying DLD using the mTRF approach can provide insights into how neural entrainment impacts various aspects of typical and atypical language development and could help uncover the neural basis of language (dis)abilities.

4.1.1 Current Study

The current analyses use EEG data freely available from the Healthy Brain Network (HBN), one of the only large-scale datasets with a combination of phenotypic and neuroimaging data. One of the challenges of this dataset is that neural recordings are shorter which decreases power and signal-to-noise ratio (SNR). This is typically done to save testing time and avoid testing fatigue. In Chapter 3, we investigated neural entrainment using a measure of coherence. However, we only found neural entrainment in a small band, which limited our ability to interpret the findings to different aspects of speech. This may be due to a limitation in power as we had slightly under three minutes of EEG data. In the current study, we added an additional video clip to increase power and we used the mTRF method which allowed us to look at how children with RD and/or DLD differentially phase-lock to acoustic and phonetic speech features.

The mTRF method may be the solution to analyzing continuous stimuli that is shorter in duration. There are two approaches for model testing; the generic approach and the subject-specific approach (Di Liberto & Lalor, 2017; Mesik & Wojtczak, 2023). In the generic approach, models are tested using the average weights and bias values of a group. In the subject-specific approach, models are tested using each individual’s weights and bias values. The generic approach has been shown to perform well on limited amounts of data and less data is required per participant when using a large participant pool (Di Liberto & Lalor, 2017; Di Liberto et al., 2018; Mesik & Wojtczak, 2023). Di Liberto & Lalor (2017) were the first to use a generic modeling approach. Overall, the subject-specific approach had greater prediction values, but the generic model showed sensitivity for the combined feature model with only 10 minutes of data. Mesik and Wojtczak (2023) went on to demonstrate that when a model is sufficiently trained on a large data set, generic models can have high performance on as little as 2-8 minutes of data. The model takes into account individual variability, but the TRFs are homogeneous. Using the generic model approach, both Di Liberto et al. (2018) and Klimovich-Gray et al. (2023) found significant differences in the neural patterns of TD and RD individuals in their models.

The first goal of this study is to extend the findings in Chapter 3 in determining whether neural entrainment to speech features can be detected with limited data. Given that this method has been shown to demonstrate neural entrainment with only two minutes of data, we hypothesize that this method will show more robust findings than those from Chapter 3. The second goal of this study is to replicate previous findings in individuals with RD by investigating neural entrainment at delta, theta, and combined delta-theta. These bands are hypothesized to be especially indicative of neural entrainment to speech at the level of syllables and words (Goswami, 2011). We extend the research by looking at the potential role of alpha since it has been linked to tracking phonological information (Keitel et al., 2018). We also extend the research by including a group of children diagnosed with DLD. We hypothesize that children with DLD will exhibit different neural responses to speech features compared to TD individuals. In addition, we hypothesize that the neural responses in individuals with DLD will be similar to those with RD since they have similar difficulties with phonological processing. Insights gained from studying these groups can inform the neural bases of these disorders as well as provide the foundation for the development of educational interventions.

4.2 Methods

Data for this study were retrieved from the Child Mind Institute's Healthy Brain Network (HBN; Alexander et al., 2017). The data used in this study include basic demographic information, behavioural and cognitive information, as well as EEG data from children listening and viewing short videos with narration and animation.

4.2.1 Participant Selection

A total of 280 children between 5-18 years (*M* = 9.74 years, *SD* = 3.08 years, 111 female) from releases 1-9 were included in this study. The three groups included were: typically developing children (TD, *n* = 134, *M* = 9.86 years, *SD* = 3.28 years, 63 female), children with specific learning disorder with impairment in reading (RD, *n* = 87, *M* = 9.50 years, *SD* = 2.68 years, 36 female), and children with language disorder (DLD, *n* = 80, *M* = 9.64 years, *SD* = 3.21 years, 19 female). There were 21 participants that were diagnosed with both RD and DLD, and this group was included in both the RD and DLD groups. To be included, children had to have official diagnoses of specific impairment in reading or language disorder as assessed by the HBN or be TD (no official diagnoses). Clinicians from the HBN made diagnoses based on the administered behavioural and cognitive tasks which were verified by two other research assistants. The Clinical Evaluation of Language Fundamentals (CELF-5) Screener (Semel et al., 1995) was used to detect children who potentially had language disorders. Further assessments, such as those evaluating expressive and receptive vocabulary, were then administered. Children were excluded if they did not have full EEG data for the videos “Fun with Fractals” and “Three Little Kittens”, and if preprocessed EEG data was not available for that participant. For more detailed information on recruitment and screening procedures, please refer to Alexander et al. (2017).

4.2.2 Behavioural Measures

To determine whether the prediction values at each frequency band were related to language and reading, we conducted correlations with the following measures. The CELF-5 Screener was used as our language measure since it was administered to every participant. We also used scores from the elision and blending words subtests and the combined score for rapid symbol naming (RSN) of the Comprehensive Test of Phonological Processing (CTOPP-2; Wagner et al., 2013). We also included the Test of

Word Reading Efficiency (TOWRE-2; Torgesen et al., 2012) Sight Word Efficiency (SWE) and Phonemic Decoding Efficiency (PDE) subtests. In addition, we included the Weschler Individual Achievement Test (WIAT III; Weschler, 2009) reading comprehension subtest as well as the composite listening comprehension plus oral discourse (LCODC) score. We also correlated sex, age, full-scale intelligence quotient (FSIQ) and working memory from the WISC-V (Weschler, 2014) with the EEG prediction values.

4.2.3 Stimuli

The EEG session included multiple tasks and stimuli. For this study, we used two video clips. “Fun with Fractals” is a 2.72-minute-long educational video clip, voiced by a female speaker (found at https://www.youtube.com/watch?v=XwWyTts06tU), and “Three Little Kittens” is a 2.85-minute-long video clip taken from the movie “Despicable Me” (found at https://www.youtube.com/watch?v=HNXxJIhVALI), which were sampled at 44,100 Hz. The first 3552 ms were removed from “Fun with Fractals” and the first 1400 ms were removed from “Three Little Kittens” since there was no speech in these first seconds of the video. This also avoids fitting the model with the neural response to the onset of the stimulus presentation (Crosse et al., 2021). Silences exceeding 3000 ms were also removed to maximize the amount of speech information in the signal. The same segments of EEG data were removed. The EEG and stimuli from the two videos were then concatenated, leading to a total of 5.17 minutes of temporally aligned speech data and EEG signals.

4.2.4 EEG Recording and Preprocessing

EEG data were recorded using a 128-channel EEG Geodesic Hydrocel system, at a sampling rate of 500 Hz with a bandpass of 0.1 to 100 Hz and recording reference at Cz. See Langer et al. (2017) for the full description of preprocessing steps. We re-referenced the data to the average of all electrodes. The data were then bandpass filtered from 0.5 to 16 Hz using a 4th order Butterworth filter, and downsampled to 100 Hz to reduce the number of time points and therefore improve model training time (as recommended by Crosse et al., 2021). All electrodes were used for the analyses.

4.2.5 Model Evaluation

4.2.5.1 Spectrogram (S)

The amplitude envelope of the video clips' audio were extracted by dividing the frequency spectrum into 16 bands logarithmically spaced from 250 to 8000 Hz. The amplitude envelopes were extracted using the Hilbert transform. They were then low-pass filtered at 40 Hz and high-pass filtered at 1 Hz using FIR filters (order 1690 and 170, respectively), and zero-phase digital filtered. To match the sample rate of the EEG, the bands were then resampled to 100 Hz with an anti-aliasing filter. Following this, the spectrogram was normalized.

4.2.5.2 Phonetic Features (F)

Following Di Liberto et al. (2017, 2018), phonetic features were extracted using the Prosodylab-Aligner software (Gorman et al., 2011). This software performs forced alignment using the audio file and transcripts with phonetic information from the American English International Phonetic Alphabet (IPA). The script returned time points for the start and end of each word and phoneme. Alignment was then manually checked and corrected. We then converted this into a multivariate time-series, where each phoneme was coded as 1-39 and they existed for as long as their occurrence. These 39 phonemes were then converted to 18 phonetic features related to the manner of articulation, place of articulation, consonant voicing, backness of a vowel, and diphthongs.

4.2.5.3 Combined F and S (FS)

We combined the phonetic and spectrographic models which resulted in a total of 34 features. This model provides an index of low-level acoustic as well as higher-level phonetic information (Di Liberto & Lalor, 2017; Lesenfants et al., 2019), which provides more information on speech tracking than each individual feature alone. It also accounts for variations in acoustic features for each phoneme since, in natural speech, the same phonemes may be spoken differently, and thus have a different spectro-temporal profile.

We used the mTRF toolbox in MATLAB (version 2020b) to construct a forward encoding model by mapping the speech features with the EEG data (Crosse et al., 2016). The weights of the model are called TRFs and are calculated by performing ridge regressions between the features and the EEG. First, the data were segmented into five subsets using the *mTRFpartition* function. Because we only had 5.17 minutes of data for each participant, we used a generic model approach, where we averaged the mTRFs across participants within each group. While this assumes a certain level of homogeneity within each group, this approach has been shown to be a more robust measure of EEG predictability (Di Liberto & Lalor, 2017; Di Liberto et al., 2018). To obtain the EEG predictions, a 5-fold cross-validation was conducted using the *mTRFcrossval* function. The optimal ridge value (λ) was used to train the model obtained via a parameter search on a range of ridge values from 10^{-5}, 10^{-3}, …, 10^{5}. The ridge value that maximized the correlation between the original and predicted EEG data was chosen. The model was trained using the *mTRFtrain* function which performs ridge regression. The TRFs are regularized which smooths the data so that the model is not overfit and decreases estimation error. We restricted our analyses to 15 Hz and below since studies using ridge regression have found that neural entrainment activity is more robust at lower frequencies (< 15 Hz) due to the low SNR in the higher frequency bands (e.g., Di Liberto et al., 2015; Lesenfants et al., 2019). Our models were then calculated at delta (1-4 Hz), theta (4-8 Hz), delta-theta (1-8 Hz), and alpha (8-15 Hz) bands.

We first used a within-group approach to directly compare the mTRFs and prediction values (using *mTRFpredict*) between the TD group with the DLD and RD groups. The EEG prediction values reflect phase-locking to each speech feature (Di Liberto et al., 2018). The hypothesis is that children with RD and DLD will have lower prediction values for prosodic and phonemic information, indicating an impairment in phase-locking at lower frequencies. For this approach, we trained separate models for each group using a leave-one-out cross-validation approach on each participant in each group at each frequency band. We then averaged this model and used the generic model to test the EEG from the left-out participant using the *mTRFpredict* function. This process was then repeated on all participants within their group. An initial time-lag window of -500 to 400 ms was selected to obtain EEG predictions for all models. Different time lag ranges were tested on the models and then narrowed to -200 to 200 ms, given where the TRFs were greatest. The models were then trained using the optimal ridge value and time-lag window. The optimal ridge value for all models was determined to be 10. Region of interest (ROI) analyses were then conducted on the areas with the greatest prediction values. As a secondary analysis, we removed the RD+DLD combined group from the RD and DLD groups to determine whether there were neural entrainment differences between these two groups. We trained separate models on these two groups in order to directly compare them. This led to a total of 59 children with DLD and 66 children with RD. The hypothesis is that there will be significant differences in neural tracking between RD and DLD.

We conducted region-of-interest (ROI) analyses on frontal electrodes since previous forward modeling studies have found that the strongest prediction values are in the fronto-central electrodes (Di Liberto et al., 2015; Di Liberto & Lalor). This region also had one of the strongest prediction values (see Figure 4.1 for selected electrodes). These electrodes were averaged and compared between groups. We also wanted to compare findings to the AST theory, therefore, we conducted separate analyses on frontal electrodes in the right hemisphere (RH) and left hemisphere (LH).

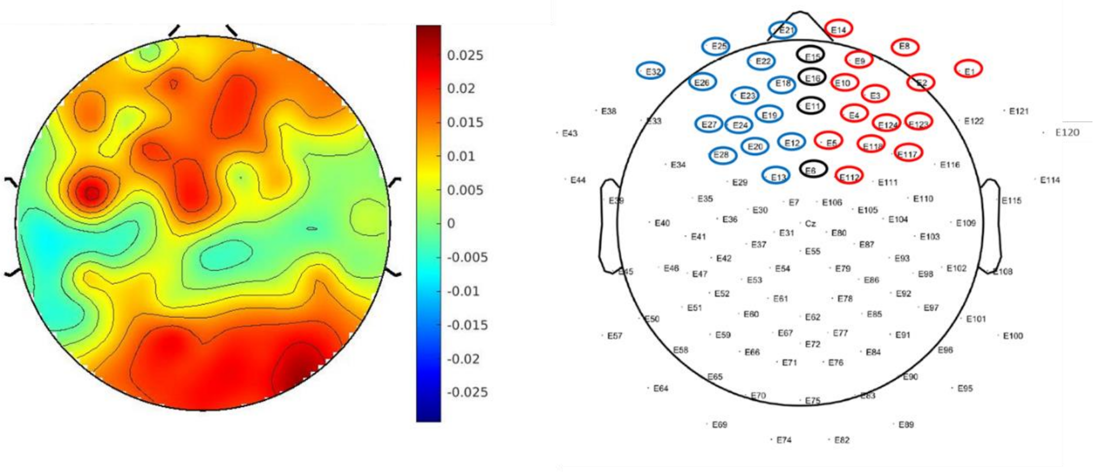

Figure 4.1. Distribution of prediction values from the FS model for all participants from 1-15 Hz (on the left), and selected electrodes for the ROI analyses (on the right). All electrodes were used in the frontal ROI analyses, blue electrodes used in the left hemisphere (LH) analyses and red electrodes used in the right hemisphere (RH) analyses.

Following this, we used the same steps as above to train and test models on all participants. This way the prediction values are not obtained from specific grouping, which allows us to see how the EEG prediction values interact with psychometric variables (like language and reading scores). We also used these models to determine which model obtained the greatest prediction values, and which frequency bands had greater values. Pearson’s correlations with language and reading scores were also conducted using the predictability indices of each model trained on all participants for each frequency band.

4.2.6 Statistics

To test if the models performed significantly above chance, one-sample t-tests against zero were conducted on all models ($\alpha < .05$). For all pairwise comparisons, we used the non-parametric Wilcoxon rank sum test. If the group was used in more than one analysis, as with the TD group, the comparisons were Bonferroni corrected ($\alpha < .025$). For three or more comparisons, the non-parametric Kruskal-Wallis test was conducted, and post-hoc comparisons accounted for family-wise error. The correlations between the reading and language scores with the EEG predictability indices were FDR corrected.

4.3 Results

4.3.1 Models Trained on All Participants

Models were run on all participants to determine which model produced the best prediction values. Better EEG prediction values correspond to stronger phase-locking between the stimulus and the EEG signal. All models performed significantly above chance ($p < .001$). There was a significant difference between model performance at delta (($\chi^2(2, 839) = 6.87$, $p = .032$); however, the post-hoc comparisons were not significant after correcting for family-wise error (see Figure 4.2a). The models were also significantly different at delta-theta ($\chi^2(2, 839) = 18.76$, $p < .001$). The post-hoc comparisons demonstrate a significant difference between the S and F models ($p = .001$) and the F and FS models ($p < .001$; see Figure 4.2c). There were no significant differences observed between the models at theta (see Figure 4.2b) or alpha (see Figure 4.2d). We also found that the delta band had significantly greater prediction values than both the theta band ($p < .05$) and the alpha band ($p < .001$) in the S and FS models. There were no significant differences between frequency bands for the F model.

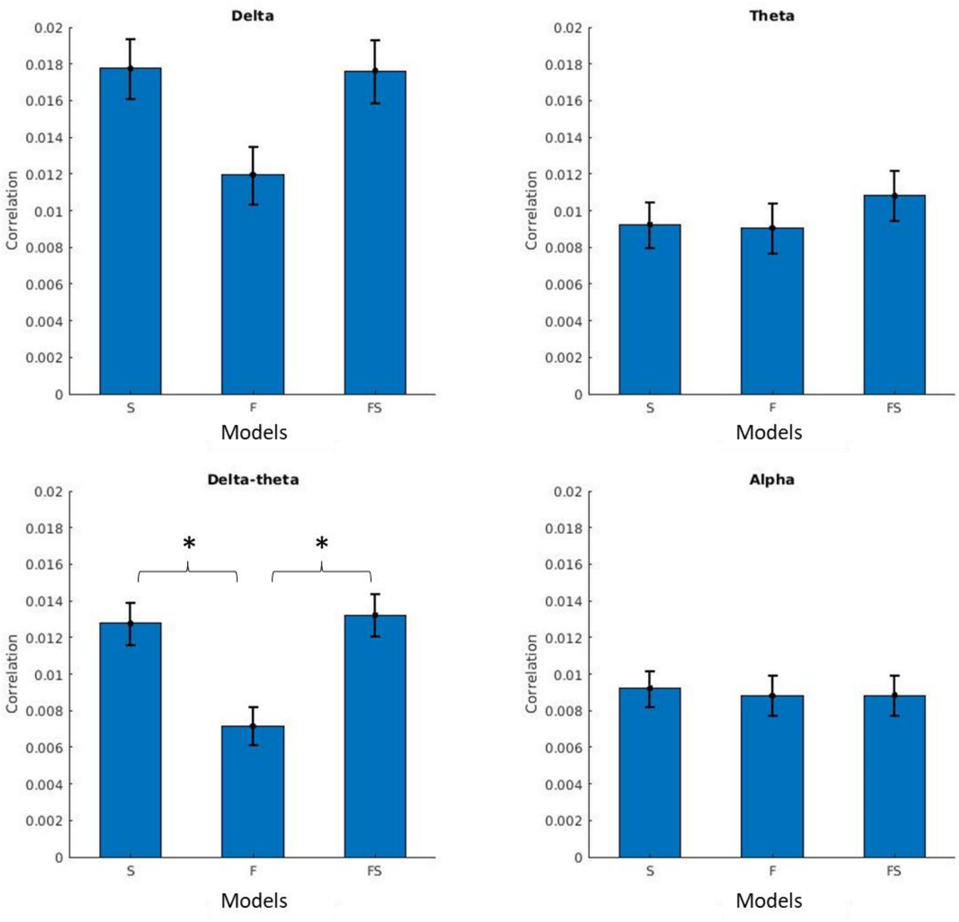

Figure 4.2. Prediction values for the S (spectrogram), F (phonetic), and FS models trained on all participants. Error bars represent standard error.

4.3.2 Group Analyses

Here, separate models were trained for the three groups, and the TD group was compared to the RD and the DLD groups to determine how well the acoustic and phonetic information is reflected by the groups' EEG signal. The comparison of EEG prediction values averaged across electrodes are presented below.

4.3.2.1 S Model

All models were significantly above chance except for RD at alpha (*t*(86) = 1.06, *p* = .290). Prediction values were significantly lower in children with DLD compared to TD children at delta (*U* = 15405, *p* = .023, *r* = .16; see Figure 4.3). There were no other significant differences between these groups at theta (*p* = .406), delta-theta (*p* = .486), nor alpha (*p* = .378). There were also no significant differences between the TD and RD groups at delta (*p* = .033), theta (*p* = .784), delta-theta (*p* = .220), or alpha (*p* = .154).

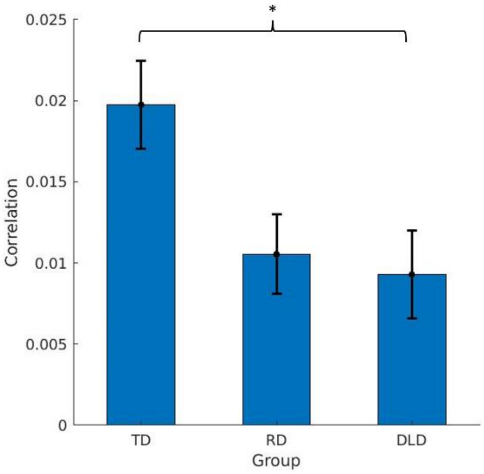

Figure 4.3. Comparison of prediction values for S (spectrogram) models at delta between the TD (typically developing), RD (reading disability), and DLD (developmental language disorder) groups. Error bars represent standard error.

4.3.2.2 F Model

Models for RD at delta-theta (*t*(86) = .95, *p* = .345) and alpha (*t*(86) = 1.31, *p* = .195) and DLD at alpha (*t*(79) = 1.03, *p* = .308) were not significantly above chance. Because of this the following results need to be interpreted with caution. The TD children had significantly greater prediction values at delta-theta (*U* = 15926, *p* = .024, *r* = .15) and alpha compared to the children with RD (*U* = 16347, *p* = .002, *r* = .21; see Figure 4.4). Alpha was also significantly greater in TD compared to DLD (*U* = 15846, *p* = .001, *r* = .22). There were no significant differences between TD and RD and TD and DLD at delta (*p* = .034; *p* = .039), and theta (*p* = .623; *p* = .878). There were also no differences between TD and DLD at delta-theta (*p* = .350).

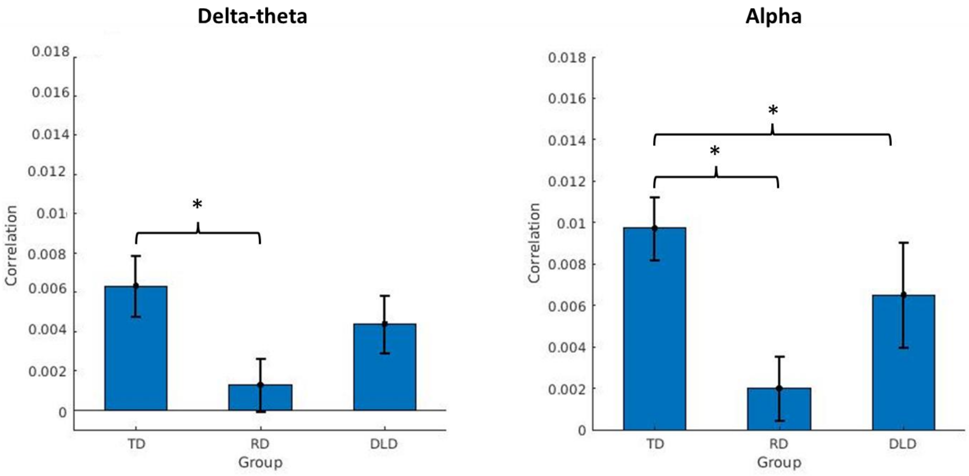

Figure 4.4. Comparison of prediction values of the F (phonetic) model at delta-theta and alpha between the TD (typically developing), RD (reading disability), and DLD (developmental language disorder). Error bars represent standard error.

4.3.2.3 FS Model

All models were significantly above zero except for RD at alpha (*t*(86) = 1.94, *p* = .055). Similar to the results from the F model, TD children had significantly greater prediction values compared to children with RD at alpha (*U* = 16404, *p* < .001, *r* = .22; see Figure 4.5). However, this effect was not observed for children with DLD (*p* = .064).

There were no other significant differences between TD and RD and TD and DLD at delta (*p* = .053; *p* = .038), theta (*p* = .657; *p* = .605), and delta-theta (*p* = .105; *p* = .436).

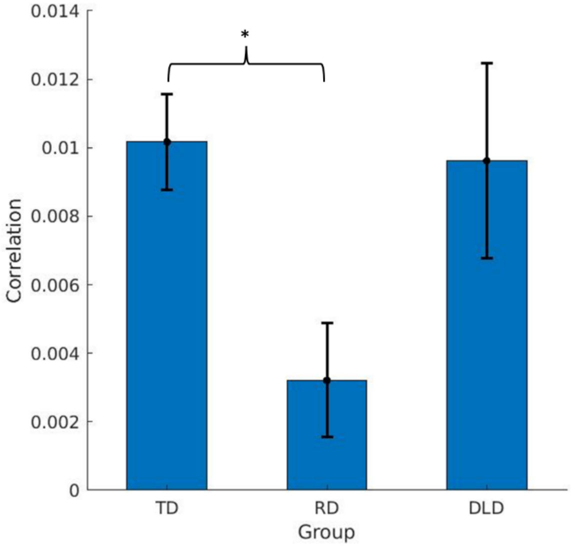

Figure 4.5. Comparison of prediction values at alpha for the FS (combined) model between the TD (typically developing), RD (reading disability), and DLD (developmental language disorder) groups. The error bars represent standard error.

4.3.3 Prediction Values between RD and DLD

These two groups were also directly compared after the removal of the 21 comorbid RD+DLD individuals. For the S model, children with RD had significantly lower prediction values at alpha compared to the children with DLD (*U* = 4177, *p* = .023, *r* = .20; see Figure 4.6). There were no significant differences at delta (*p* = .769), theta (*p* = .321), or delta-theta (*p* = .538). For the F model, children with RD had significantly lower prediction values at delta-theta compared to children with DLD (*U* = 4116, *p* = .049, *r* = .18; see Figure 4.7). There were no significant differences between the two groups for the F and the FS models at delta (*p* = .803; *p* = .478), theta (*p* = .519; *p* =

.528), and alpha (*p* = .391; *p* = .186). Delta-theta was also not significantly different for the FS model (*p* = .175).

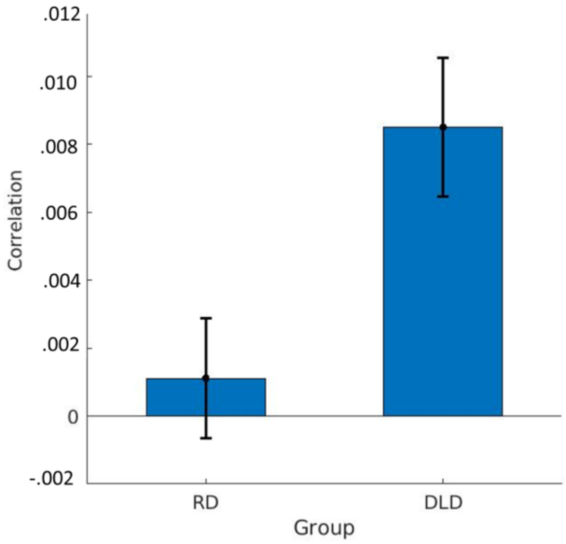

Figure 4.6. Comparison of prediction values for the S (spectrogram) model at alpha between the children with DLD (developmental language disorder) and RD (reading disability). Error bars represent standard error.

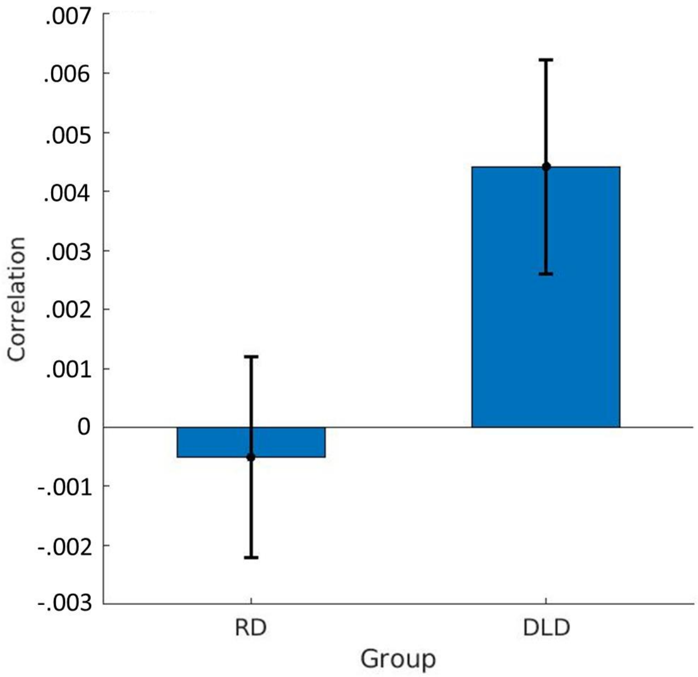

Figure 4.7. Comparison of prediction values for the F (phonetic) model at delta-theta between the children with DLD (developmental language disorder) and RD (reading disability). Error bars represent standard error.

4.3.4 ROI Analyses

See Figure 4.8 for the results of the S model comparisons, Figure 4.9 for the F model comparisons, and Figure 10 for the FS model comparisons. All models demonstrated that TD children had significantly greater prediction values at alpha in the frontal electrodes compared to children with RD (S: $U = 1415$, $p = .003$, $r = .20$; F: $U = 1497$, $p < .001$, $r = .27$; FS: $U = 1417$, $p = .003$, $r = .20$). Alpha in the RH was also significantly greater for TD compared to RD in all models (S: $U = 306$, $p = .003$, $r = .20$; F: $U = 311$, $p = .001$, $r = .22$; FS: $U = 313$, $p < .001$, $r = .22$) as well as the LH for the F model only ($U = 293$, $p = .013$, $r = .17$). Further, the F model also demonstrated that TD children had greater prediction values compared to children with DLD at alpha ($U =$

1394, *p* = .007, *r* = .18) and in the RH at alpha (*U* = 311, *p* = .001, *r* = .22). The S model was the only one that demonstrated that TD children had greater values at delta-theta than children with RD (*U* = 1402, *p* = .005, *r* = .19) and DLD (*U* = 294, *p* = .011, *r* = .17). The S and FS models also demonstrated greater RH entrainment in TD vs RD at delta-theta (S: *U* = 305, *p* = .003, *r* = .20; FS: *U* = 294, *p* = .011, *r* = .17). Even though there were no overall significant differences at delta between TD and RD in the frontal electrodes, RH entrainment was greater for TD at delta in all models (S: *U* = 293, *p* = .013, *r* = .17; F: *U* = 290, *p* = .02, *r* = .16; FS: *U* = 287, *p* = .025, *r* = .15). A similar result was found in the S model for children with DLD, who had significantly lower prediction values than TD children in the RH at delta (*U* = 288, *p* = .023, *r* = .16). No other models were significantly different (*p* > .025).

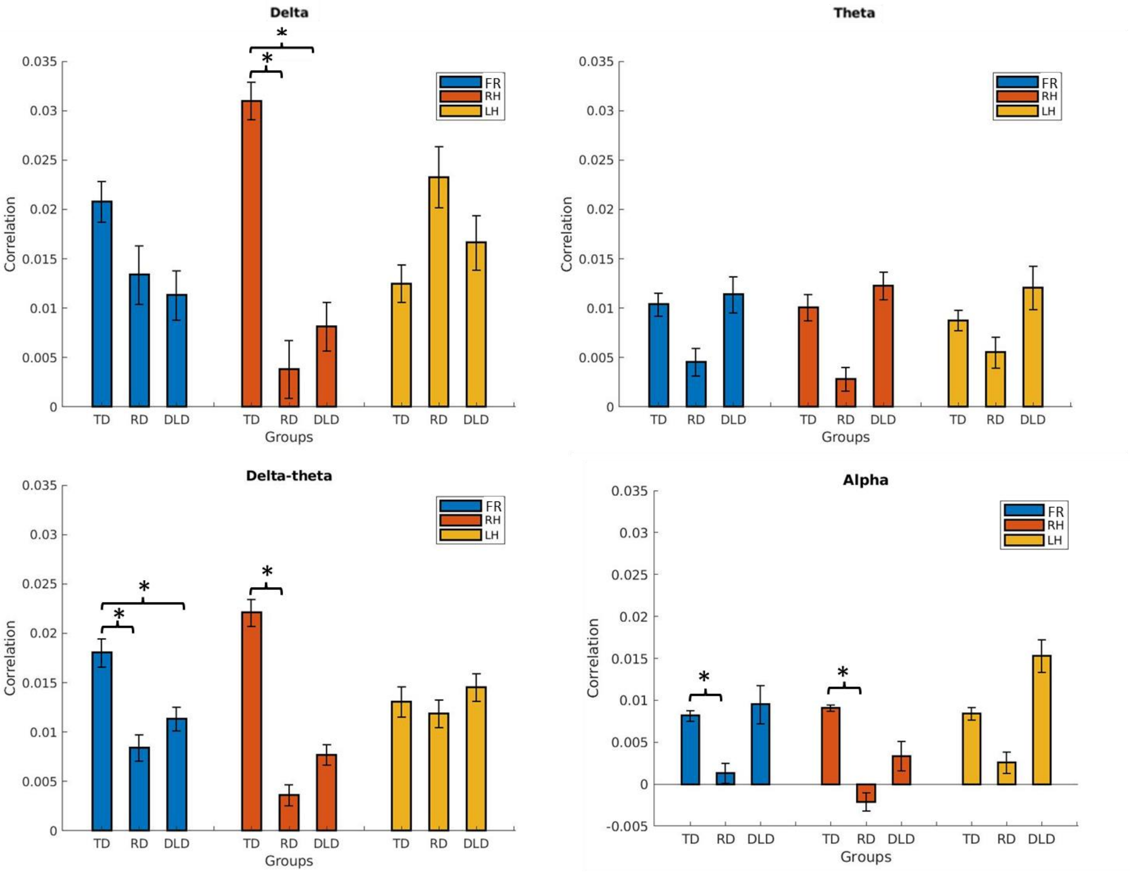

Figure 4.8. Comparison of prediction values for the S (spectrogram) model for each group at frontal (FR), right hemisphere (RH), and left hemisphere (LH) electrodes. Error bars represent standard error.

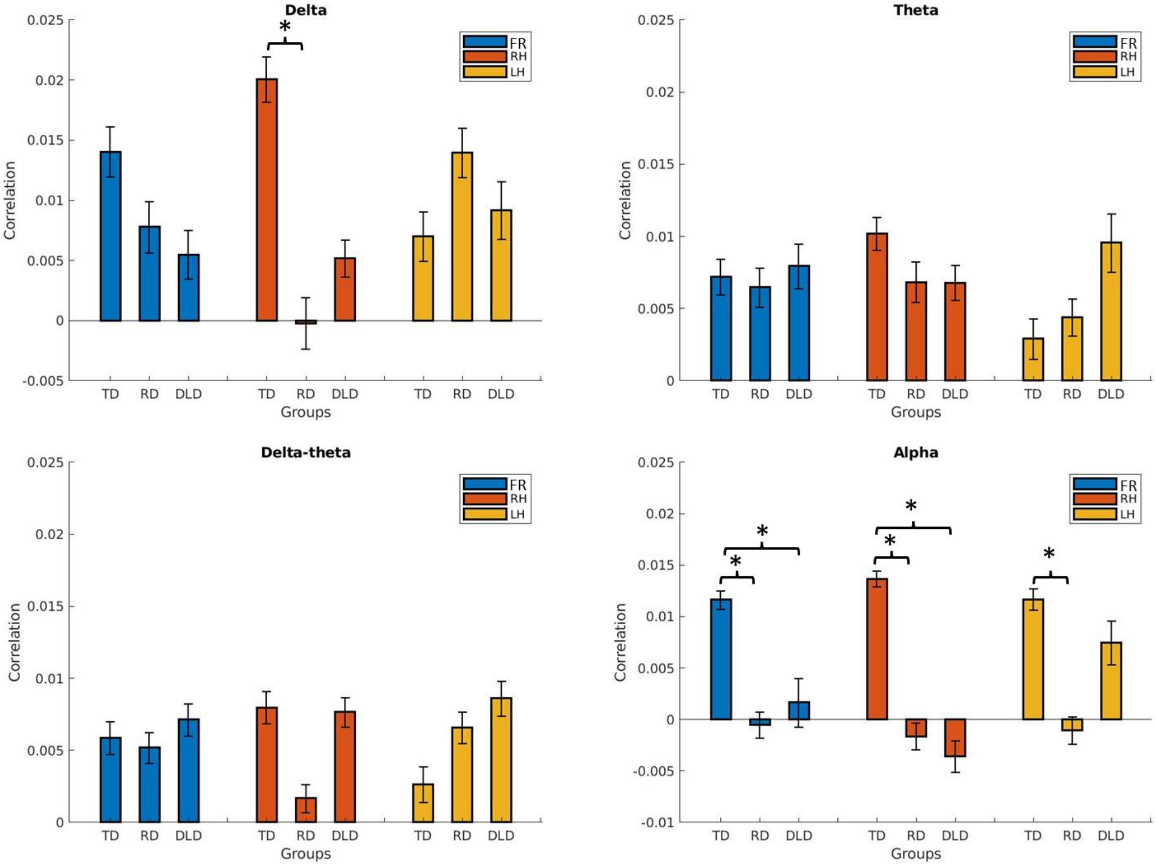

Figure 4.9. Comparison of prediction values for the F (phonetic) model for each group at frontal (FR), right hemisphere (RH), and left hemisphere (LH) electrodes. Error bars represent standard error.

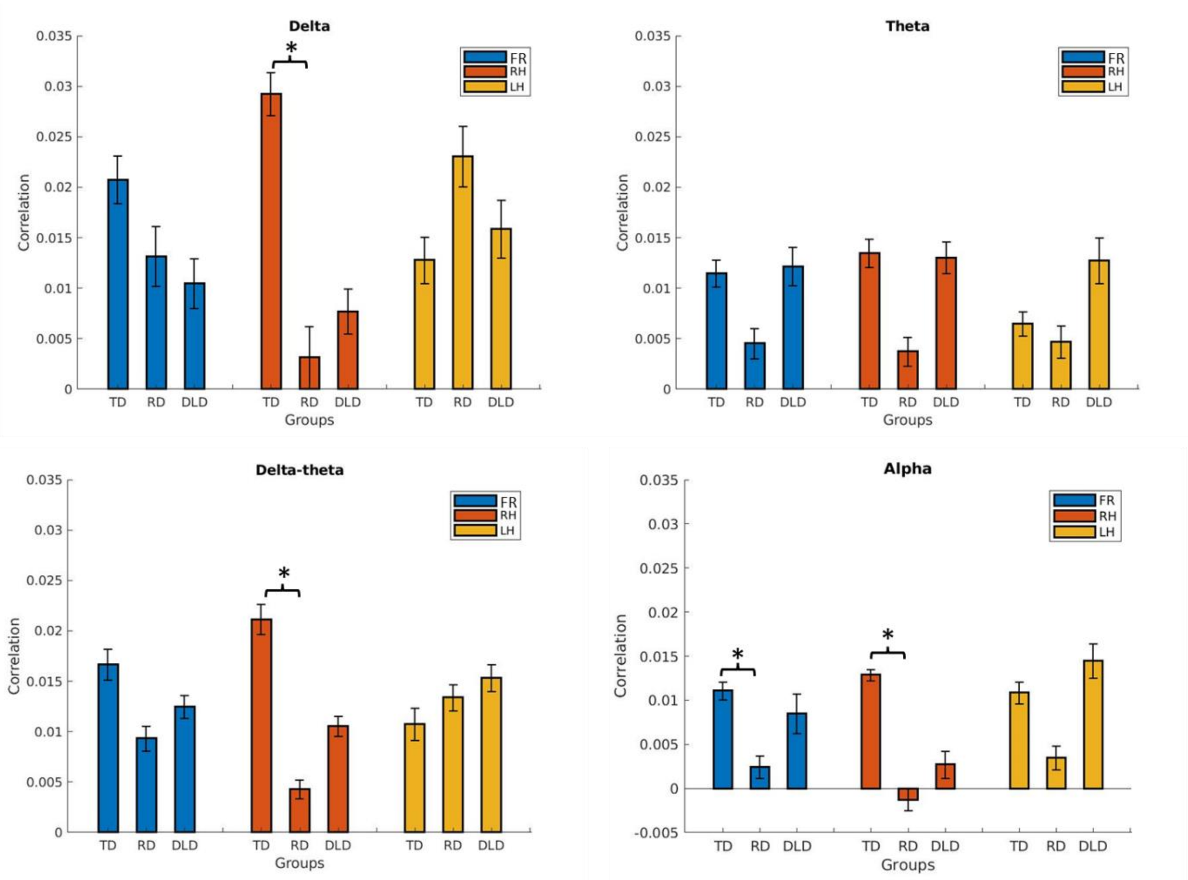

Figure 4.10. Comparison of prediction values for the FS model for each group at frontal (FR), right hemisphere (RH), and left hemisphere (LH) electrodes. Error bars represent standard error.

4.3.5 Correlations

Correlations were conducted between the prediction values obtained from training on all participants for all models. None of the correlations were significant after FDR correction (see Appendix B).

4.4 Discussion

In this study, we assessed neural entrainment of EEG to speech using forward encoding models, comparing children with reading disability (RD), developmental language disorder (DLD) and typically developing children (TD). The prediction values obtained from models can be seen as a representation of the strength of phase-locking. Our goals were to 1) determine whether EEG neural entrainment could be detected with only five minutes of data, and 2) determine whether there were significant differences in the neural patterns of TD children compared to those who have difficulties in phonological and language processing. Below, we discuss our findings.

4.4.1 Model Comparisons

We trained the models on all participants using a cross-validation approach and compared the models' ability to predict EEG data from missing participants. We found that neural entrainment to the spectrogram and phonetic features could be detected above chance with as little as five minutes of EEG data. These findings demonstrate the utility of the mTRF approach as it is not always possible to gather longer neural recordings from children. It is generally better to have more data per participant as EEG predictability performance increases with more data, especially for the sparser models (like the F model; Mesik & Wojtczak, 2022). However, this is not always feasible, especially with younger children and clinical populations. In our case, we could not collect our own data due to pandemic restrictions and had to rely on an already existing dataset with limited data. These findings show that even when data collection (or longer data collection) is not possible, we can still obtain meaningful results that contribute to scientific advancement.

Past studies have demonstrated that combining phonetic and acoustic features in model training improves EEG model predictions (Di Liberto et al., 2015, 2018). We sought to determine whether this held true for our models, which looked at acoustic features (S model), phonetic features (F model) and the combination of both features (FS model). We found that there were no significant differences between the models at delta, theta, and alpha. However, at delta-theta, we found that the S and FS models had significantly greater values than the F model. It is possible that the F model had significantly lower prediction values because 23% of the included recording did not have phonetic information. This could have led to a decrease in the F model's performance and the non-significant difference between the FS and F models. Further, Mesik and Wojtczak (2023) found that peak prediction accuracies in models with a sparse amount of data (such as the F model) were lower than the denser S model. The addition of phonetic information in the model did not seem to add enough meaningful information to increase the performance of the FS model. It is possible that our F model does not capture the full complexity of the speech sounds as well as the S model.

We also looked at the specific frequency bands and found that delta had greater prediction values than theta and alpha in the S and FS models but not the F model. This may be because delta oscillations are related to processing acoustic information present in both S and FS models. Delta oscillations are particularly important as they are related to speech and non-speech processing of acoustic information, including rhythm, tone, and syllable stress (Ding & Simon, 2014; Goswami, 2011). The cues processed by delta oscillations are important for successful syllable parsing and thus language comprehension.

4.4.2 Group Findings

Our main goal was to determine whether children with RD and DLD had different neural patterns compared to TD children to acoustic and/or phonetic information. Di Liberto et al. (2015, 2018) demonstrated that there was a direct link between poor neural entrainment at lower frequency bands and phonological processing. We sought to replicate these findings and extend them by including children with DLD. We also investigated whether neural patterns differed based on ROIs (frontal electrodes, including RH and LH). Our results demonstrate different patterns for each model.

The S model was the only one in which we found significant differences in the average prediction values at delta, with DLD having lower values than TD children. The ROI analyses demonstrated there was significantly lower delta in the RH in frontal electrodes for the children with DLD and RD. This is similar to findings in dyslexia of lower RH entrainment (Molinaro et al., 2016; Klimovich-Gray et al., 2023). This demonstrates that there is a similar deficit at delta in entraining acoustic information between individuals with RD and DLD.

Interestingly, we did not find significant differences in any of the models at theta. This is similar to Di Liberto et al.'s (2018) findings of greater group differences at delta and combined delta-theta bands. In addition, they found that there was an overall reduction at delta-theta in all speech models in RD for all electrodes. We also found this reduction in the F model and the frontal ROI for the S model. In addition, we found lower frontal RH values for the S and FS models in RD. These findings demonstrate that there is weaker prosodic and phonetic tracking in children with RD. This is primarily related to less specialized lateralization which is differentially affected by the speech features tracked (i.e., phonetic and acoustic). These findings also demonstrate the importance of the frontal brain region in speech processing. The frontal region has also previously been demonstrated to differ between RD and TD children (e.g., Di Liberto et al., 2018; Dushanova et al., 2020). Our models demonstrate that the lower entrainment in the RH in the frontal regions affect processing at multiple levels (prosody, syllables, phonemes). Indeed, greater entrainment in the RH at delta and theta has been related to better reading and phonological processing (Abrams et al., 2009; Lizarazu et al., 2015). These findings are in accordance with many other studies indicating that children with RD have less specialized brain network organization for speech tracking (e.g., Di Liberto et al., 2018; Hämäläinen et al., 2012; Lehongre et al., 2013; Lizarazu et al., 2015, 2021; Molinaro et al., 2016; Destoky et al., 2022; Mandke et al., 2022). These findings also provide further evidence for the AST, demonstrating the importance of the RH for speech processing. As for findings in DLD, the models demonstrated lower delta-theta in the frontal electrodes in these children compared to the TD group for the S model only. This demonstrates weaker processing of prosodic information in DLD. The findings highlighted above demonstrate the complexities of neural tracking of speech information across models and populations.

Average EEG prediction values at alpha were also significantly lower in DLD compared to TD children in the F model and lower in RD compared to TD in the F and FS models. When we looked at frontal electrodes, children with RD had lower prediction values compared to TD in all models and children with DLD had lower values in the F model. These findings demonstrate that entrainment differences at alpha are primarily in the frontal region. Further, children with RD primarily had lower alpha values in the RH compared to TD children, and lower LH values for the F model. The F model also demonstrated significantly lower phase-locking in the RH in the frontal region for children with DLD. These findings demonstrate that, at alpha, children with RD may have deficits entraining to acoustic and phonetic information, and children with DLD may have deficits primarily to the phonetic information. We also found two important differences between children with RD and DLD. Children with RD had lower neural entrainment at delta-theta to phonetic information and at alpha to the spectrogram compared to DLD. This may demonstrate that these groups process acoustic and phonetic information differently, with RD demonstrating a greater impairment in neural entrainment. These findings are the first to demonstrate such a difference in neural entrainment. However, behavioural tasks have demonstrated that there are no differences in auditory processing between RD and DLD (e.g., Caccia & Lorusso, 2019; Corriveau et al., 2007). There is a need for more neural research to better understand the underlying differences in speech tracking impairments in RD and DLD.

It is important to note that EEG prediction values were not significantly greater than zero at alpha in all models and delta-theta for the F model for children with RD and the F model at alpha for children with DLD. For this reason, the interpretation of the results needs to be done cautiously. One possible explanation is that children with RD and DLD have a high variability in how they process speech features, which may make it challenging for the models to identify consistent neural patterns. In fact, the children with RD and DLD were more heterogeneous than the TD children as they had comorbidities with other disorders. An alternative, but not mutually exclusive, explanation is that the lower EEG prediction values may reflect poor phase-locking in RD and DLD to acoustic and phonetic information. The findings may imply that children with DLD, and especially RD, have less synchronized neural responses to speech features in comparison to TD.

Most of the differences between groups were found at alpha. This is interesting because previous studies have not focused much of their attention on this frequency band. Because of this, not as much is known about speech entrainment at alpha, but there are a couple of studies that have linked alpha with phoneme tracking (Keitel et al., 2018; Vanden Bosch der Nederlanden et al., 2022). In addition, some studies have found that individuals with RD have less alpha entrainment than TD (De Vos et al., 2017; Granados Barbero et al., 2021; Van Hirtum et al., 2020), and this is related to lower phonological awareness scores (De Vos et al., 2017). This would indicate that the alpha frequency band represents weaker phoneme tracking in RD and DLD. Another theory for alpha entrainment is that it is related to the gating of sensory information, optimizing information processing (Cabral-Calderin & Wilke, 2020; Klimesch et al., 2007). This means that alpha inhibits irrelevant neural activity allowing the brain to focus resources on task-relevant information. In addition, when alpha oscillations are more synchronized, they can reduce interference of task irrelevant information and optimize the timing of neural firing. Because alpha oscillations are not as strong in children with RD and DLD, this may mean that cognitive resources are not being efficiently allocated such that irrelevant information is interfering with the timing and synchronization of the relevant information (e.g., neural responses related to speech tracking vs. neural responses related to background noise). This would affect the successful parsing of speech features, affecting overall speech comprehension.

Although there were differences in findings between our models and Di Liberto et al.'s (2018), our findings and theirs demonstrate that children with RD track speech differently than TD children. The findings of impaired speech tracking in RD are in accordance with a multitude of studies that have found varying deficits in speech tracking in children with RD (e.g., Abrams et al., 2009; Hämäläinen et al., 2012; Keshavarzi et al., 2022). These findings are in accordance with the TSF (Goswami, 2011) demonstrating that children with RD and DLD have weaker neural entrainment to lower frequencies compared to TD children. In addition, our study was the first to demonstrate impaired speech tracking in children with DLD at lower frequencies, in line with the TSF. Two previous studies have also demonstrated that neural entrainment in DLD is impaired compared to TD individuals (Heim et al., 2011, 2013), but this was at the gamma frequency band. Together, these findings demonstrate weaker neural entrainment to multiple timescales, providing evidence for both the TSF and RAP. These findings could be used to inform interventions targeting improved speech comprehension. For instance, Heim et al. (2013) demonstrated promising gains in neuronal activity and oral language measures after implementing a language intervention program targeting RAP skills.

4.4.3 Correlations

After FDR correction, none of the reading and language measures were related to prediction values in any of the models. Some of our findings concurred with Di Liberto et al.'s (2018) in that IQ and RSN were not related to prediction values. However, Di

Liberto et al. (2018) found that greater phase-locking (i.e., stronger prediction values) to phonetic and acoustic features (FS model) was related to better phonological and language skills. We may not have had enough power to detect significant effects. Di Liberto et al. (2018) had nine minutes of data per participant whereas we had five minutes of data. However, previous findings on whether neural entrainment is correlated with language and reading are mixed. For instance, Lizarazu et al. (2021) did not find any significant correlations between their measure of neural entrainment at delta and gamma with reading, phonological abilities, and rapid automatized naming (RAN, similar to RSN) whereas Soltész et al. (2013) found that neural entrainment at delta was positively correlated with reading and phonological processing. There were also different correlational findings between studies based on the group and specific ROI. De Vos et al. (2017) found that neural entrainment at alpha in TD was positively correlated with phonological processing, and neural entrainment at beta in RD was positively correlated with phonological processing. Further, Molinaro et al. (2016) did not find any correlations between neural entrainment at delta in the right auditory cortex with reading, phonological processing and TOWRE; however, delta in the left inferior frontal gyrus was positively correlated with SWE in RD only. In summary, neural entrainment may be related to aspects of language and reading, but may vary depending on multiple factors, including the sample specifics and stimuli. More replication studies with greater power are needed to better understand the relationship between language and reading with neural entrainment.

4.4.4 Limitations and Future Directions

An inherent limitation of this study is that we did not have the original stimulus file, meaning that the EEG data and stimulus did not align perfectly at the millisecond level. We were given the time stamps for the YouTube videos in seconds, and not milliseconds. Thus, we trimmed the videos using this information, which could have led to inconsistent timing between the EEG and stimuli files. When calculating for the best time lag in each model, there was a large difference between the optimal time lag for the S model compared to the F model. This could have contributed to the lower prediction values for our F models, especially in the RD and DLD groups. However, a large time lag range could lead to overfitting of the models which is why we committed to using a smaller time lag range. To better understand the role of neural entrainment in children with DLD and RD, future studies should use longer audio files with a rich amount of phonetic information in order to increase power and confidence in the findings.

It is also important to acknowledge the use of generic models. These models are trained on each individual and then tested using the average weights and bias values of all participants within a group. Using this approach is advantageous as models can be trained with small amounts of data and produce similar results to the subject-specific models, which are tested on individual participants' weights and bias values. However, generic models assume within-group homogeneity which may not be as suitable for differentiating neural patterns in clinical populations (Di Liberto & Lalor, 2017). Subject-specific models require more data per participant for sparser models (~17 minutes) but as little as 5 minutes for denser models. Both model types have their utility, and their limitations need to be considered when using them, especially for differentiating clinical populations. TRF models have much potential for diagnostic applications. However, much more research is needed in this area before it can be used in a diagnostic capacity.

One of the biggest advantages of TRFs is that they can be analyzed in various ways providing critical information on neural entrainment to speech (see Crosse et al., 2021 for examples). For instance, decoding models could be used to determine how different groups decode stimulus features based on neural activity (e.g., Destoky et al., 2022). TRFs can also be used to evaluate a model's ability to generalize across participants and different parts of a dataset. This approach has many advantages over the approach used in Chapter 3 (cerebro-acoustic phase coherence), which could only detect phase-locking to a narrow frequency range and could not detect differences between groups. Encoding models are also relatively easy to compute with the help of the mTRF toolbox, relatively fast if downsampled, and easy to interpret. TRFs offer a comprehensive approach to studying neural entrainment to speech, providing valuable insights into the neural dynamics across populations.

An interesting avenue for future research would be to investigate how forward encoding model predictions differ in children with DLD and RD across different languages. Past studies have demonstrated that the presentation of DLD and RD across languages differs based on multiple factors such as the language's orthographic transparency (Borleffs et al., 2019) and grammatical differences (Leonard, 2014). By studying this, we can better understand how neural entrainment to different speech features relate to and impact DLD and RD across languages. Once we have a better understanding of neural entrainment in different languages, we can better tailor intervention programs. For instance, rhythm-based training programs show some promise in improving children’s prosodic, reading, and phonological processing abilities (Fiveash et al., 2021; Habib et al., 2016).

4.4.5 Conclusions

Our results provide valuable insights into how neural entrainment to speech is modulated based on whether children have language or reading impairments. Our findings replicate previous studies’ findings demonstrating weaker neural entrainment to acoustic and phonetic information in children with RD and DLD compared to TD children. This deficit is especially present in the RH, also replicating findings providing further evidence for the AST theory. Our study was also the first to find neural entrainment differences in children with DLD compared to children with RD and TD children at lower frequency bands. Additionally, we also investigated the importance of the alpha frequency band, demonstrating that children with RD and DLD have lower alpha entrainment, potentially impacting speech comprehension and information processing. This study demonstrates the utility of forward encoding models in assessing neural entrainment differences with limited amounts of data per participant. This study demonstrates the complexities of neural tracking in RD and DLD and provides avenues for further research which could improve children’s language and reading abilities.

4.5 References

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Chapter 5

5 General Discussion

Reading disability (RD) and Developmental Language Disorder (DLD) collectively affect 14% of the population (Bishop, 2010; Peterson & Pennington, 2012). Even given this level of prevalence, there is still much we do not understand about the cognitive underpinnings of these disorders. One hypothesis is that individuals with RD and DLD have poor neural entrainment to auditorily presented speech information (Goswami, 2011; Richards & Goswami, 2015; Tallal & Piercy, 1973). Neural entrainment in this context is the alignment of auditory information (such as the amplitude envelope) with neuronal activity, which may be oscillatory in nature. There are peaks and troughs in both signals and neural entrainment approaches quantify the alignment of the amplitude and/or phase of these two signals across time and frequencies via neuroimaging methods (Gross et al., 2013). When these two signals do not align, this could lead to difficulties in speech processing and comprehension (Riecke et al., 2018; Zoeffel et al., 2020). Theories posit that atypical alignment of neuronal oscillations to the speech signal is related to problems with phonological processing, a common difficulty in RD and DLD (Catts et al., 2005; Goswami, 2011; Richards & Goswami, 2015). In this dissertation, neural entrainment is used in the broad sense, meaning that these studies investigate the alignment of brain and stimulus information irrespective of whether the generating mechanism is oscillatory in nature (Obleser & Kayser, 2019). The primary goal of this dissertation is to gain a better understanding of RD and DLD by examining how the synchronization of neural activity to speech relates to language and reading abilities.

I first conducted a systematic review to summarize and understand neural entrainment in individuals with RD and DLD (Chapter 2). In the following chapters, I addressed some of the gaps highlighted in Chapter 2. In Chapter 3, I investigated neural entrainment using a measure of coherence in children with a spectrum of language and reading abilities. In Chapter 4, I sought to use a measure of neural entrainment that would demonstrate more robust findings, and, therefore, used forward encoding models. In the following sections, I summarize the key findings and draw connections between them and to the broader literature. Finally, I discuss the dissertation's implications as well as future directions.

5.1 Summary of Findings

I first conducted a systematic review of neural entrainment that compared RD or DLD with typically developing (TD) individuals. The most apparent takeaway from this review was the lack of studies available on neural entrainment in DLD. DLD in general is an understudied disorder, with even less information available on their neural patterns (McGregor, 2020). To better understand the cognitive patterns underlying DLD, more studies are needed. The two studies that did look at this group found weaker neural entrainment in DLD vs TD at beta-gamma, related to the faster elements of speech processing, such as phonemes (Heim et al., 2011, 2013). Importantly, one of the studies found promising gains in neuronal activity and oral language measures for their intervention program targeting RAP skills (Heim et al., 2013). More research, especially research focusing on intervention programs like the one by Heim et al. (2013), is crucial for the advancement of knowledge and improving outcomes for individuals with DLD.

There was little consensus across frequency bands for neural entrainment patterns in RD vs TD, except at delta. Delta is related to non-speech-specific processing, including prosodic information. Most of the studies found that individuals with RD had weaker delta entrainment (Abrams et al., 2009; Di Liberto et al., 2018; Dushanova et al., 2020; Hämäläinen et al., 2012; Keshavarzi et al., 2022; Lizarazu et al., 2021a; Mandke et al., 2022; Molinaro et al., 2016; Soltész et al., 2013). The other frequency bands likely had varying results due to the different methodological choices across studies. One of the biggest takeaways from the review was that there is no standard for measuring neural entrainment. Different types of stimuli and approaches to quantifying neural entrainment were used which shaped these studies' results. Studies using stimuli with temporally regular acoustic cues, such as amplitude-modulated white noise (e.g., Doelling et al., 2014; Rufener & Zaehle, 2021), have greater power because of the repeated stimulus and can inform us about entrainment at specific stimulus presentation frequencies. The information gained from these studies is foundational. However, naturalistic speech can provide information relevant to real-world speech tracking making it more ecologically valid. The review concluded with the recommendation of measuring neural entrainment using continuous speech, which is a better representation of the complexity of spoken language.

The goal for the third chapter was to address the two main gaps highlighted in the review: 1) to look at neural entrainment in children with various language and reading abilities, including children with DLD and RD, and 2) to use more ecologically valid stimuli. I used the Healthy Brain Network's (HBN) data because they had behavioural and electroencephalography (EEG) data for hundreds of children, including children with

RD and DLD, which is not always easy or quick to collect. Furthermore, the stimulus they used was natural speech. The only caveat was that the stimuli they had available were short 2-3 minutes video clips. Cerebro-acoustic phase coherence (CAPC) was measured to a 2.75-minute-long video. The results demonstrated significant neural entrainment to the spoken stimuli in this clip, within a narrow band corresponding to theta. This demonstrates that the children were entraining to syllabic information, crucial for successful speech comprehension (Ding & Simon, 2014; Giraud & Poeppel, 2012). However, neural entrainment was not significant in any of the other bands. CAPC is likely not sensitive enough to detect neural entrainment to other speech features because of the shorter nature of the stimuli.

This was the motivation for the fourth chapter. I sought to use a method of neural entrainment that was sensitive even with a limited amount of data per participant. I added an additional clip containing 2.45 more minutes of data to increase power and signal-to-noise ratio (SNR). For this project, I used forward encoding models which have been shown to be sensitive to as little as two minutes of data (Mesik & Wojtczak, 2023). Just as in Chapter 3, there were no significant differences found between groups for theta entrainment. The systematic review in Chapter 2 also revealed several studies that have not found significant differences between RD and TD at theta (De Vos et al., 2017a, 2017b; Di Liberto et al., 2018; Fiveash et al., 2020; Han et al., 2012; Keshavarzi et al., 2022; Molinaro et al., 2016; Poelmans et al., 2012; Power et al., 2013; Van Hirtum et al., 2019). These findings suggest that individuals with RD and DLD extract syllabic information from speech to a similar level as TD individuals. However, some studies suggest that the alpha frequency band is related to the upper limit of syllabic processing and/or phonemic processing and that less accurate encoding is occurring at this band (De Vos et al., 2017b; Keitel et al., 2018; Vanden Bosch der Nederlanden et al., 2022; Van Hirtum et al., 2019). To test this idea, I compared EEG prediction values in the alpha band between RD, DLD, and TD. Alpha entrainment was indeed significantly lower in children with RD to both acoustic and phonetic information whereas children with DLD had significantly lower entrainment to only the phonetic information. This demonstrates less accurate encoding of phonetic information at alpha. These findings are also in line with a few studies that have also found lower alpha entrainment in RD (De Vos et al., 2017b; Granados Barbero et al., 2021; Van Hirtum et al., 2019), which has also been related to lower phonological awareness (De Vos et al., 2017b).

Interestingly, RD had weaker alpha entrainment to acoustic information in comparison to DLD. Further, children with RD had lower values than DLD at delta-theta to phonetic information. The weaker neural entrainment at alpha to acoustic information in children with RD vs DLD may suggest that these children have more profound challenges in the neural processing of acoustic information related to phoneme timing. Individuals with RD and DLD both have deficits in auditory processing, but the nature of these deficits may differ. Individuals with RD may struggle more with processing rapidly presented acoustic information related to phonemes, while individuals with DLD may more broadly struggle with processing and understanding rapid acoustic changes in speech. The reduced neural entrainment to phonological information at delta-theta indicates that children with RD may have more profound challenges decoding speech sounds than children with DLD. Children with RD primarily struggle with phonological processing (Bishop & Snowling, 2004) whereas children with DLD have deficits in multiple areas of language including, phonology, semantics, morphology, and syntax (Bishop et al., 2017). We could gain a better understanding of the underlying impairments in RD and DLD by looking at differences in encoding multiple levels of speech features. For instance, neural entrainment to semantics can also be modeled using forward encoding models (Van Uden et al., 2018).

In Chapter 4, I also looked at neural entrainment at delta and the combined delta-theta bands to replicate previous findings by Di Liberto et al. (2018) and to add to the body of literature reported in Chapter 2. Children with RD had lower delta-theta entrainment to acoustic and phonetic information, which is in line with past findings (e.g., Di Liberto et al., 2018). In addition, children with DLD had weaker neural entrainment compared to TD for acoustic information only. This suggests that impairments in low-frequency tracking is related to poorer encoding of acoustic information in both groups as well as phonetic information for children with RD. Only children with DLD had lower delta to acoustic information compared to TD children. This is the first study to show lower neural entrainment at delta in children with DLD, demonstrating impaired speech tracking to prosodic information. However, there were no significant differences at delta between RD and TD, which is not in line with the findings from Chapter 2 nor Di Liberto et al. (2018). There are various possibilities as to why previous findings were not replicated. The participants from the HBN were heterogeneous, including comorbidities with other disorders such as attention deficit hyperactivity disorder (ADHD). Neural entrainment is proposed to underlie selective attention (see Calderone et al., 2014 for a review; O’Sullivan et al., 2015) which suggests that individuals with ADHD would have different patterns of neural entrainment compared to TD. Children with comorbidities were included to increase power and the generalizability of the results as children with RD and DLD are likely to have comorbidities in the real world (Bishop et al., 2017; Hendren et al., 2018). For this reason, it is important not to exclude children with comorbidities; however, this is a likely reason for the differences in results.

Another goal was to test the findings from Chapter 2 for the Asymmetric Sampling in Time (AST; Poeppel, 2003) theory in Chapter 4. This theory posits that there should be greater right hemisphere (RH) activity for slower rates (delta, theta) and greater left hemisphere (LH) activity for faster rates (beta, gamma; Giraud & Poeppel, 2012; Poeppel, 2003). To test this theory for the slower rates, I conducted region-of-interest (ROI) analyses in the left and right hemispheres for the frontal electrodes. In Chapter 2, most studies looking at lateralization found that individuals with RD had lower RH lateralization at delta and theta (this was not explored at alpha). In Chapter 4, there was weaker delta and alpha activity in the RH for RD and DLD, and weaker delta-theta in the RH for RD. These findings provide new information demonstrating that individuals with RD and DLD have weaker neural entrainment in the RH at alpha. In addition, these findings are mostly in accordance with the findings in Chapter 2, demonstrating reduced RH entrainment at lower frequencies for those with RD (Destoky et al., 2022; Di Liberto et al., 2018; Hämäläinen et al., 2012; Lehongre et al., 2013; Lizarazu et al., 2015, 2021b; Mandke et al., 2022; Molinaro et al., 2016). Greater RH entrainment is related to better reading and phonological processing (Abrams et al., 2009; Lizarazu et al., 2015), indicating that reduced entrainment in the RH to low frequencies may be directly related to poor reading and phonological processing skills. In summary, these findings provide further evidence for the AST, demonstrating the importance of the RH for speech tracking at lower frequencies.

Finally, I conducted correlations between neural entrainment and measures of language and reading in Chapters 3 and 4. None of these correlations were significant after correction for multiple comparisons. The summarized correlational findings in Chapter 2 demonstrate mixed findings at delta and theta. Five studies did not find any significant correlations (De Vos et al., 2017a, 2017b; Lizarazu et al., 2021b; Mandke et al., 2022; Poelmans et al., 2012), but several other studies did find significant relationships at delta and/or theta using different measures of neural entrainment (Abrams et al., 2009; Colling et al., 2017; Destoky et al., 2022; Di Liberto et al., 2018; Halliday et al., 2014; Keshavarzi et al., 2022; Lizarazu et al., 2015, 2021a; Molinaro et al., 2016; Soltész et al., 2013; Zhang et al., 2021). The significant correlations varied depending on the ROIs used, tasks, and grouping of participants. Some of the studies did not correct for multiple comparisons which could have led to spurious findings. This goes back to the discussion in Chapter 2, in which more methodological consensus is needed across studies to better understand the bigger picture of whether there is a relationship between language and reading skills and neural entrainment.

5.2 Implications and Future Directions

The different patterns of neural entrainment in RD and DLD, especially to acoustic and phonetic information, suggest potential avenues for differentiating these two groups. This could have practical implications for improving the accurate diagnosis of these populations and tailoring interventions based on their specific areas of impairment. Additionally, these findings have important theoretical implications. The findings provide support for the TSF (Goswami, 2011) in that the findings demonstrate atypical neural entrainment at delta in individuals with RD and DLD. However, the lack of atypical entrainment at theta challenges the TSF. Although the TSF does not discuss the alpha band, alpha entrainment was found to be atypical for RD and DLD in Chapter 4, demonstrating its relevance. While the RAP theory (Tallal & Piercy, 1973) was not directly tested in Chapters 3 and 4, the evidence summarized in Chapter 2 suggests atypical neural entrainment at beta and gamma. This suggests that individuals with RD and DLD have difficulties with the rapid presentation of stimulus information, aligning with RAP findings. The results also support the AST showing lower RH activity in RD and DLD at delta (Chapter 2, 4), theta (Chapter 2), and alpha (Chapter 4). These findings reinforce the importance of the RH, especially frontal RH, in speech tracking. In Chapter 2, the findings at gamma align with the AST in that individuals with RD had lower LH activity, more important for speech tracking at higher frequencies. However, the findings at beta challenge the AST in that most studies found lower RH activity in RD.

This dissertation demonstrates that alpha may play a more important role than previously thought, demonstrating a relationship between alpha and processing of phonetic information. Alpha is also thought to be important for verbal working memory (Meyer, 2018), and is hypothesized to inhibit irrelevant neural activity allowing the brain to focus resources on task-relevant information, such as acoustic and phonetic information (Cabral-Calderin & Wilke, 2020; Klimesch et al., 2007). However, this project could not directly test this relationship. To uncover alpha’s role in neural entrainment to speech, alpha oscillations could be manipulated using techniques such as transcranial alternating current stimulation (tACS) while doing tasks related to verbal working memory. Alpha tACS has been shown to be causally related to working memory (Borghini et al., 2018), but the connection to speech entrainment has not been established. More research is needed on alpha oscillations to better understand its role in language processing.

One important limitation to note in both Chapters 3 and 4, is the unequal sample sizes for the group comparisons. Specifically, there were significantly more TD participants than participants with RD and DLD. Statistical power may be compromised, which would make it difficult to detect true group differences and increase Type I error rates (Rusticus & Lovato, 2019). A solution to this issue would be to conduct subsample analyses to reduce the number of participants in the TD group to be closer to the number of participants in the RD and DLD groups.

An important avenue for future work is to focus on neural patterns in individuals with DLD. I emphasized in Chapter 2 the importance of a more comprehensive exploration into neural entrainment in DLD. Further, Chapter 2 is a good reference for future research and the effect sizes calculated can be used in future meta-analyses. Meta-analyses were not possible in this project because of the level of heterogeneity across studies. Once there are enough studies that use similar methodologies, meta-analyses can be conducted to better understand neural entrainment in RD and DLD. Meta-analyses provide us with one effect size which would allow us to more clearly visualize differences in neural entrainment in RD and DLD. This would also facilitate the identification of within-study factors contributing to the differences observed across studies, offering a comprehensive understanding of neural entrainment. This could also lead the way to more methodological consensus across studies.

Other than the findings summarized in Chapter 2, I did not explore associations with higher frequency bands (i.e., beta and gamma). Atypical beta and gamma have been hypothesized to be related to the disruption of the successful processing of phonemic features (Giraud & Poeppel, 2012). However, the method used in Chapter 3 (CAPC) could not detect significant neural entrainment beyond theta and the method used in Chapter 4 (encoding models) has low SNR at beta and gamma (Di Liberto et al., 2015; Lesenfants et al., 2019). Most studies looking at beta and gamma have used non-speech stimuli, but there are a handful of studies that have looked at neural entrainment to words (Dushanova et al., 2020), sentences (Han et al., 2012), and continuous speech (Lizarazu et al., 2021b; Mandke et al., 2022). It is important to look at neural entrainment to continuous speech in order to make the findings generalizable to actual speech processing. Magnitude squared coherence and cross-correlation capture the relationship between two signals and have been shown to be sensitive beyond the theta range (Dushanova et al., 2020; Lizarazu et al., 2021b; Mandke et al., 2022). Cross-correlation provides phase and amplitude information of two signals given a time lag and the magnitude squared coherence provides information on the phase and the magnitude of the correlation between two signals at different frequencies. Both approaches are useful and provide different information on how two signals align. ITC between brain regions has also been shown to be a useful measure in the higher frequency ranges because it demonstrates functional coupling between regions (Han et al., 2010; Mandke et al., 2022). These three indices of neural entrainment seem to be promising measures which could provide useful information on neural entrainment at beta and gamma.

The three studies discussed in this dissertation provide a clearer picture of the patterns of neural entrainment in RD and DLD. Further, this dissertation presents novel data on neural entrainment in DLD and at alpha, both often understudied in this area. This dissertation has important methodological, theoretical, and practical implications. Although there are still many questions that remain, this dissertation provides a solid foundation for future work.

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Appendices

Appendix A: Full Summary for Each Frequency Band in the Systematic Review

Group Comparisons

Delta. Although results varied, 53% of studies investigating delta indicated that children and adults with RD had significantly worse neural entrainment than TD individuals to stimuli, spanning from white noise and tones to sentences and stories (SID 1; SID 6; SID 7; SID 9; SID 28; SID 15; SID 29; SID 17; SID 20). An additional 37% of studies showed no significant differences in overall neural entrainment; however, other noteworthy distinctions between groups were uncovered (SID 2; SID 25; SID 8; SID 12; SID 16; SID 19; SID 32). Only one study reported no differences between groups (SID 31). Importantly, methodological variations contributed to variations in results.

Five studies showed that individuals with RD had poorer neural entrainment than TD individuals in the RH, while individuals with RD showed more bilateral activity (SID 6; SID 9; SID 16; SID 17; SID 25). Children with RD also displayed less efficient right-lateralized functional connectivity, measured using graph theory in two studies (SID 29; SID 17). The right auditory cortex was directly related to low coherence in the left inferior frontal gyrus (IFG), leading to lower overall neural entrainment in two studies (SID 7; SID 17). Children with RD also exhibited atypical cross-correlation with shorter peak lags at delta-theta, earlier preferred phase at delta, and reduced phase consistency compared to TD children (SID 2; SID 19; SID 28). These findings suggest children with RD synchronize less efficiently to informative information in the signal, and have less specialized lateralization, which could impact speech tracking and phonological processing.

Importantly, neural entrainment results differed based on the methods used (e.g., neural entrainment analysis, stimuli, language, population). Three of the studies mentioned above found differences in cross-correlation but not in inter-trial coherence (ITC) and auditory steady-state response (ASSR; SID 2; SID 16; SID 19). Similarly, using the same participants, individuals with RD had poorer ITC to pseudowords (SID 32), but there were no group differences revealed by phase lag index (PLI) and graph theory analyses (SID 31). These measures assess distinct aspects of neural entrainment, which may contribute to differing outcomes. Laterality also differed when different methods were used (i.e., combined EEG and fMRI; SID 12), and when different features were examined (i.e., speech edges vs. overall neural entrainment; SID 15). Continuous speech also yielded differences between groups (SID 29) but not trisyllabic words (SID 31). Since connected speech is more ecologically valid, it is more generalizable to speech processing in the real-world. In four studies, differences in neural entrainment were found only in challenging listening conditions (i.e., irregular rhythms, speech with noise, compressed speech) and not in the clear or regular listening conditions (SID 1; SID 8; SID 25). This could be due to the regular speech conditions having a stronger beat or rhythm than the irregular and noisy conditions, which would be more difficult to track, especially in RD.

Theta. Twenty studies examined differences in the theta range. Results varied across studies; five studies reported significant group differences (SID 25; SID 26; SID 22; SID 14; SID 16), and another five studies reported group differences in laterality but not in overall neural entrainment (SID 9; SID 12; SID 29; SID 31). Ten studies reported no differences (SID 4, SID 5; SID 6; SID 8; SID 10; SID 28; SID 17; SID 18; SID 19; SID 21). As discussed below, this inconsistency may be attributed to the type of stimuli and measures used, groups examined, and age.

Among the studies that did not find significant group differences, several measures were used including ASSR, ITC, cross-correlation, coherence, phase consistency, preferred phase, and graph theory. The authors provided several possible explanations for why there were no group differences, including a lack of sensitivity to capture group differences. SID 4 and 6 did not find significant differences in ASSR, but group differences were detected using source activity reconstruction (SID 26 and SID 27). Source activity reconstruction provides components with the most phase-locked activity which may be a more precise measure of ASSR. SID 19 hypothesized that their non-significant results were due to the rate of presentation of their stimuli (2 Hz rather than 4 Hz). This was also the case for SID 8 and SID 28. However, this cannot explain the other non-significant findings where stimuli were sentences or 4 Hz AM white noise (SID 10; SID 17; SID 18; SID 21). SID 25 did not find differences in neural entrainment in RD and TD children of the same age; however, younger TD children had lower neural entrainment compared to children with RD, potentially indicating that the differences observed are due to age and not neural entrainment. Forward encoding models revealed no group differences at theta (SID 6). However, combined delta-theta (1-8 Hz) showed the most pronounced differences, with greater entrainment in TD children. Delta was the main driver, demonstrating that theta plays a role in language processing, but is less significant compared to delta.

Seven studies found that neural entrainment was right dominant in TD adults and children and more bilateral in individuals with RD (SID 9; SID 12; SID 14; SID 17; SID 25; SID 29; SID 31). Since the RH is more attuned to processing syllabic rates than the LH (Poeppel, 2003), these findings suggest less specialized brain network organization at theta in individuals with RD (see Fraga-González et al., 2018).

One study investigated longitudinal effects of neural entrainment in RD and TD children (SID 27). TD 5- and 9-year-olds had greater connectivity and ASSR compared to children with RD, demonstrating better syllabic-rate processing. However, the 7-year-olds did not demonstrate a difference in ASSR, possibly due to RD children's higher neural effort during the period when intensive reading training is conducted. The 5- and 7-year-old TD children exhibited more RH lateralization compared to children with RD, aligning with previous findings of more RH lateralization in TD individuals (Poeppel, 2003). SID 22 found that older children (~12 years) with RD had greater ITC than age-matched TD participants when responding to large and small deviants during an oddball detection task. The younger children (~9 years) with RD had greater ITC to only small deviants, which may indicate that children with RD are adopting compensatory mechanisms as they get older due to the lack of hemispheric specialization. Finally, two studies suggested stronger compensatory mechanisms may come into play with maturation as TD adults and adolescents had lower ASSR and ITC at 4 Hz compared to those with RD (SID 15; SID 26), which could indicate a reliance on 4 Hz syllabic-rate information.

Alpha. Eight studies investigated differences in the alpha band. Five of these studies did not find significant differences in alpha between groups (SID 9; SID 10; SID

16; SID 26; SID 31), and SID 28 found that there was no consistent phase entrainment in either group. However, some studies did find differences for specific stimulus types and analytic techniques: ASSR and neural connectivity (as assessed through coherence between denoising source separation components) were greater in TD adolescents for left ear stimulation, and neural connectivity was greatest in adolescents with RD for right ear stimulation (SID 26). ASSR was also greater in TD adolescents versus adolescents with RD (SID 4), and in TD adults for rise times of 10 and 30 ms (SID 21). These findings support the view of limited differences in alpha entrainment between TD and RD individuals.

Beta. Thirteen studies looked at the beta band. Nine studies found significant differences between groups which varied based on the methods used (SID 4; SID 5; SID 7; SID 14; SID 18; SID 21; SID 24; SID 26; SID 27; SID 29). Three studies found no significant group differences in ITC, amplitude cross-correlation, phase lag index, and network topology (SID 9; SID 16; SID 31).

One study found that TD adults had greater ASSR compared to adults with RD for slower rise times (30 ms; SID 21), indicating that individuals with RD have reduced sensitivity to the phonemic rate. Conversely, adolescents with RD had greater ASSR when ears were stimulated separately (SID 4) and greater ASSR and neural connectivity for right ear stimulation than TD adolescents (SID 26). These findings indicate the impact of stimulation methods on neural entrainment.

A few studies found different results based on hemisphere or electrode region. ASSR and coherence were lower in RD adults in the LH (SID 18); however, phase of beta power was different between groups in electrodes over the right auditory cortex (SID 24). This difference in asymmetry between studies could be due to the different frequency range or electrodes selected. SID 24 focused on 15-25 Hz in the auditory cortices, while SID 18 focused on 20 Hz in parietal and mastoid electrodes. Moreover, beta activation has been found to be right-lateralized in more frontal electrodes and left-lateralized in more posterior locations in individuals with RD (Spironelli et al., 2008), which could also contribute to the divergent findings. SID 29 used a larger range (12-40 Hz) and found that TD children only had greater coherence in the occipital region compared to children with RD. SID 7 looked at the differences between groups at all electrodes and found that children with RD exhibited greater coherence to words in the RH which could be associated with compensation due to the overall inefficient encoding of phonemic information. Greater entrainment in certain brain areas in children with RD may represent a compensatory mechanism that is not as efficient as TD children's phonological encoding. The atypical asymmetry demonstrates less specialized lateralization in individuals with RD, linked to reading and phonological processing difficulties (Spironelli et al., 2008).

Longitudinal studies showed varying results. ASSR was greater in 7- and 9-year-old children with RD, with no significant difference between 5-year-olds (SID 5). However, source reconstruction in the same participants found decreasing ASSR with age in children with RD compared to TD children (SID 27), suggesting that TD children develop better phonological representations which may lead to greater ASSRs in comparison to children with RD. Neural connectivity patterns also differed, with TD children demonstrating greater connectivity at 7-years-old, and children with RD demonstrating greater connectivity at 9-years-old. This may indicate that compensatory mechanisms in children with RD are related to enhanced phoneme rate processing. Further, the LI indicated that there was a stronger right lateralization in 5- and 7-year-olds with RD, but not at 9-year-olds, suggesting a late maturation of beta since previous results demonstrate that TD adolescents (SID 4; SID 26), and adults (SID 21) exhibit symmetric neural entrainment.

Gamma. Fourteen studies examined neural entrainment in individuals with RD, and, for the first time, two studies examined neural entrainment in children with DLD.

RD. Four of the fourteen studies found no significant differences in neural entrainment between groups (SID 4; SID 10; SID 14; SID 18). Four found that TD individuals had greater gamma neural entrainment than individuals with RD (SID 16; SID 12; SID 30; SID 21), while one study found the reverse (SID 26). SID 3 also found greater neural entrainment in TD over RD in beginners but not in advanced readers. Results were mixed for SID 7 and 13.

SID 4 found no significant differences in ASSR at 40 Hz; however, differences emerged after using source activity reconstruction (SID 26; see below). Three studies found no differences in ASSR and coherence at 60 Hz (SID 14) and 80 Hz (SID 3; SID 18). SID 10 found no overall differences in ITC between brain regions at 30-45 Hz to phonologically similar and dissimilar sentence endings. SID 30 found greater ASSR in TD children indicating undersampling of phonemic acoustic information in children with RD. This might mean that children with RD are insufficiently processing acoustic information, negatively affecting their phonemic representations (Giraud & Poeppel, 2012).

Interestingly, when specific frequency ranges are investigated, a pattern begins to emerge. SID 7 looked at multiple electrodes and frequency ranges and found that individuals with RD undersample in the LH but oversample in electrodes near the right auditory cortex at 30 Hz. At 40 Hz and above, individuals with RD had greater coherence compared to their TD peers. One other study also found greater entrainment for the individuals with RD at 40 Hz, specifically in the RH (SID 13). There was also overall greater ASSR at 40 Hz and 50 Hz in individuals with RD (SID 13; SID 26). Undersampling of the acoustic information was found to occur at low gamma in the LH in individuals with RD (SID 12; SID 13; SID 16). Greater non-synchronized neural activity in the RH was related to lower ASSR at 40 Hz in individuals with RD (SID 21), potentially linked to atypical phonemic representations (Hancock et al., 2017). Oversampling could be a compensatory mechanism to cope with lower LH neural entrainment. However, this oversampling does not seem to benefit individuals with RD as there is too much phonemic information to be integrated, possibly affecting short-term memory (Giraud & Poeppel, 2012), and leading to incorrect processing of phonemic units and poor phonological representations.

DLD. SIDs 11 and 23 investigated the beta-gamma frequency range and found that children with DLD had reduced ITC to the second of two tones compared to TD children (SID 11; SID 23), suggesting a temporal processing deficit to rapid rates. In SID 23, a subset of children from SID 11 underwent the Fast ForWord Language training program (Scientific Learning Corporation, 2001) to improve oral and written language performance. Despite still having reduced ITC to the second tone compared to TD children, children with DLD demonstrated greater ITC gains and improvements in all oral language measures after training. Interestingly, gamma power normalized between sessions wherein the second tone was no longer significantly lower in children with DLD. This suggests there was increased neuronal recruitment (Lachaux et al., 2005) related to learning gains from the training program.

Brain-Behaviour Correlations

The results presented below are for all participants combined (i.e., RD and TD), unless otherwise specified. There were no correlations reported in studies examining individuals with DLD.

Delta. Ten studies examined the link between delta and language and reading abilities. TD children, who had stronger neural entrainment, exhibited better TOWRE, and phonological processing scores (SID 2; SID 28; SID 19; SID 32). Notably, correlations were specific to auditory entrainment, as no significant correlations were found in the visual condition and few in the auditory-visual condition (Power et al., 2013). Importantly, ITC at 2 Hz, but not 1.5 Hz, positively correlated with phonology and reading (SID 20), indicating that the relationship between these measures and neural entrainment is specific to the syllable presentation rate. Surprisingly, ASSR was negatively correlated with the reading subscale of the British Ability Scales (BAS; Elliott et al., 1996) and TOWRE (SID 2). This is the opposite of other findings which may indicate that ASSR has the opposite relationship to reading compared to the other neural entrainment measures.

SID 6 reported significant positive correlations between neural entrainment with phonological awareness and phonological memory from CTOPP in the RH, which was the largest scalp area that distinguished the RD group from controls. This indicates a strong link between atypical neural entrainment and phonological processing abilities. The models were also positively correlated with TOWRE and subtests of the CELF, but not in specific ROIs.

For RD participants, MEG coherence in the left IFG was positively correlated with sight-word reading (SWE) subtest of TOWRE (SID 17). Further, connectivity strength from right auditory cortex to left IFG positively correlated with phonological awareness, potentially indicating defective feedforward functional connectivity related to phonological impairments. ITC in the left temporal regions positively correlated with reading accuracy but negatively correlated with pseudoword reading time (SID 15), suggesting greater effort in grapheme-phoneme mapping, typically impaired in RD.

Correlations with RAN were inconsistent. RAN negatively correlated with neural entrainment in one study (SID 20), positively correlated in two (SID 28; SID 32), and not correlated in another (SID 6). SID 16 and SID 29 reported multiple correlations but were not significant after corrections for multiple comparisons. There were also no significant correlations between phonological processing and ASSR power, phase (SID 2), or ITC (SID 15), nor between reading and word-rate ITC (SID 32).

Theta. Seven studies examined the link between theta and reading abilities. Greater phase-locking and magnitude asymmetry correlated with better reading and phonological processing (SID 1), indicating weak neural entrainment at theta is related to weak reading abilities. Later lags in the LH, seen in good readers, also led to better reading scores. Similarly, LI was positively correlated with word and pseudoword reading times in TD participants (SID 14), with faster times related to more right lateralization. Altogether, these results demonstrate the importance of RH lateralization at theta.

Additional findings linked poorer reading-related abilities with poor neural entrainment. ITC to small deviants in the oddball task negatively correlated with nonword repetition, driven by higher ITC scores and lower nonword repetition scores in the RD group (SID 22). Phrasal CTS (2-8 Hz) negatively correlated with RAN in the RH only, attributed to the lower RAN abilities in children with more severe RD (SID 25).

Multiple studies failed to find significant correlations between ASSR, phase consistency, preferred phase, ITC, and coherence with RAN, reading, and phonological processing (SID 4, SID 5; SID 18; SID 28; SID 32).

Alpha. Two studies looked at correlations in alpha. In TD participants, 10 Hz response amplitude positively correlated with phonological awareness in one study (SID 4). Both studies showed no significant correlations between ASSR and reading (SID 4; SID 21).

Beta. Four studies looked at the link between beta entrainment and reading abilities. ASSR and a measure of graph theory were not significantly correlated with reading or RAN in children, adolescents, and adults (SID 4; SID 5; SID 21; SID 31), nor phonological awareness in adults (SID 21; SID 31). However, phonological awareness was positively correlated with 20 Hz ASSR in adolescents with RD (SID 4), and coherence in adults (SID 18). In children, 20 Hz ASSR response amplitude negatively correlated with reading, phonological awareness, and RAN (SID 5), demonstrating that children with RD, who had the largest developmental increase in response amplitudes, had the poorest phonological and reading skills. Lower 20 Hz ASSR for slower rise times was related to worse literacy skills (SID 21). These results suggest that children with RD, who have lower coherence, ASSR, and a greater increase in 20 Hz response amplitudes, have poorer phonological, literacy and reading skills. However, greater ASSR in RD was related to better phonological awareness.

Greater LI at 30 Hz (more LH lateralization) positively correlated with errors in repeating pseudowords in adults, but not in children. However, LI did not correlate with reading, phonemic awareness, and phonological short-term memory (SID 14). Cross-correlation at 30 Hz also did not correlate with phonological processing nor with RAN after corrections for multiple comparisons (SID 16).

Gamma. Six studies looked at the relationship between gamma entrainment and reading abilities. Literacy, phonological awareness, and RAN were negatively correlated with 40 Hz ASSR neural background activity (SID 21). This indicates that poorer reading and phonological skills are related to higher neural background activity, which can reduce neural entrainment in low gamma, thereby affecting phonological processing (Hancock et al., 2017). Individuals with a higher peak gamma had greater phonological awareness skills (SID 30), indicating that RD children’s ability to pick up on temporally relevant information in the speech signal is compromised.

Reading fluency was positively correlated with 30 Hz ASSR bilaterally in TD participants, and positively correlated with low gamma asymmetry (left-dominant) in all participants (SID 13). Phonological processing negatively correlated with low gamma asymmetry in participants with RD and positively correlated in TD participants. These findings demonstrate that LH dominance in low gamma is related to better reading fluency and phonological skills. The correlations also demonstrate that increased activity in the RH led to worse RAN scores. There were no significant correlations with 30 Hz LI (SID 14) and cross-correlation in the left auditory cortex (SID 16) after corrections for multiple comparisons. The disparities between studies may be due to the use of different neural entrainment measures (ASSR vs. ITC and cross-correlation) or the age focus (narrow vs. broad range).

High gamma (45-65 Hz) ASSR negatively correlated with verbal working memory in participants with RD (SID 13). Since participants with RD oversample at this rate, a consequence might be that the auditory system picks up overly detailed acoustic information which may then affect encoding and parsing of the speech signal. ASSR was not correlated with RAN or reading fluency (SID 13), and coherence at 80 Hz was not correlated with phonological awareness (SID 18).

Appendix B : Correlations between EEG prediction values and behavioural measures

Table S 1. Correlations between the EEG prediction values and the behavioural measures at each frequency band for the S model. Significance is presented before and after FDR correction.

	Delta	Theta	Delta-theta	Alpha

Behavioural Measures	r	p	p_{FDR}	r	p	p_{FDR}	r	p	p_{FDR}	r	p	p_{FDR}
Age	.07	.274	.469	-.01	.837	.955	.04	.549	.719	-.06	.314	.616
Sex	.02	.754	.822	-.14	.021	.251	-.04	.506	.719	-.02	.745	.812
FSIQ	.11	.091	.271	-.08	.227	.680	.04	.552	.719	.16	.016	.198
WM	.13	.049	.199	-.06	.340	.762	.05	.462	.719	.08	.241	.578
CELF	.12	.040	.199	-.05	.445	.762	.06	.308	.719	.007	.903	.903
Blending	.04	.587	.704	-.12	.053	.316	-.12	.060	.359	.05	.431	.646
Elision	.05	.478	.641	-.09	.181	.680	-.07	.281	.719	.10	.119	.461
RSN	.006	.925	.925	-.004	.954	.954	-.06	.382	.719	.11	.097	.461
PDE	.11	.114	.274	-.02	.786	.954	.02	.737	.804	.06	.359	.616
SWE	.05	.481	.641	-.01	.888	.954	-.04	.599	.719	.10	.154	.461
LCODC	.16	.012	.143	-.04	.533	.800	.13	.035	.359	-.02	.744	.812
RC	.09	.141	.281	-.05	.424	.762	.01	.848	.848	.02	.705	.812

Table S 2. Correlations between the EEG prediction values and the behavioural measures at each frequency band for the F model. Significance is presented before and after FDR correction.

	Delta			Theta			Delta-theta			Alpha		
Behavioural Measures	r	p	p_{FDR}	r	p	p_{FDR}	r	p	p_{FDR}	r	p	p_{FDR}
Age	.01	.811	.826	-.02	.782	.806	-.03	.583	.670	-.09	.125	.213
Sex	-.01	.826	.826	-.11	.059	.353	-.05	.432	.670	.03	.645	.704
FSIQ	.15	.026	.109	-.06	.395	.765	.08	.248	.670	.18	.007	.059
WM	.15	.022	.109	-.05	.444	.765	.06	.379	.670	.14	.032	.126
CELF	.12	.043	.128	-.02	.702	.806	.05	.427	.670	.007	.902	.902

Blending	.05	.407	.543	-.15	.023	.279	-.04	.551	.670	.05	.461	.553
Elision	.09	.167	.326	-.08	.194	.765	.03	.676	.670	.09	.150	.213
RSN	-.04	.557	.668	.02	.735	.806	.03	.614	.670	.11	.079	.189
PDE	.09	.178	.326	-.05	.467	.765	.05	.462	.670	.12	.071	.189
SWE	.09	.216	.326	.02	.806	.806	.06	.444	.670	.18	.009	.059
LCODC	.14	.027	.109	-.05	.426	.765	.06	.310	.670	.09	.151	.213
RC	.08	.218	.326	-.04	.510	.765	.04	.508	.670	.09	.159	.213

Table S 3. Correlations between the EEG prediction values and the behavioural measures at each frequency band for the FS model. Significance is presented before and after FDR correction.

	Delta			Theta			Delta-theta			Alpha		
Behavioural Measures	*r*	*p*	p_{FDR}	*r*	*p*	p_{FDR}	*r*	*p*	p_{FDR}	*r*	*p*	p_{FDR}
Age	.06	.335	.533	-.02	.747	.933	.01	.860	.860	-.09	.125	.213
Sex	.03	.669	.731	-.12	.037	.365	-.06	.357	.778	.03	.646	.704
FSIQ	.11	.087	.238	-.07	.258	.766	.05	.432	.778	.18	.007	.059
WM	.14	.033	.132	-.07	.319	.766	.05	.464	.778	.14	.032	.126
CELF	.14	.024	.132	-.03	.602	.903	.07	.278	.778	.007	.902	.902
Blending	.04	.532	.638	-.12	.061	.365	-.10	.134	.778	.048	.461	.553
Elision	.05	.399	.533	-.08	.211	.766	-.06	.367	.778	.09	.150	.213
RSN	.01	.876	.876	.005	.933	.933	-.04	.519	.778	.11	.08	.189
PDE	.11	.099	.238	-.01	.868	.933	.02	.809	.860	.12	.07	.189
SWE	.06	.385	.533	.02	.825	.933	-.02	.723	.860	.18	.009	.059
LCODC	.15	.017	.132	-.05	.455	.903	.13	.045	.536	.09	.151	.213

RC	.08	.246	.492	-.04	.597	.903	.02	.804	.860	.09	.159	.213

Curriculum Vitae

Education

In progress **PhD, Psychology**, Western University, London, ON

- Thesis Topic: Neural entrainment to speech in children with reading and language disorders
- Supervisor: Dr. Marc Joanisse

2019 **M.Sc., Psychology**, Western University, London, ON

- Thesis Topic: Neural entrainment indexes statistical learning in children
- Supervisor: Dr. Marc Joanisse

2016 **B.Sc., Psychology**, University of Ottawa, Ottawa, ON

- Thesis topic: The effects of mobile media use on language acquisition in monolingual and bilingual infants
- Supervisor: Dr. Christopher Fennell

Publications

Parks, K., M. A., Hannah, K., **Moreau, C. N.,** Brainin, L., Joanisse, M. F. (2023). Language abilities in children and adolescents with DLD and ADHD: A scoping review. *Journal of Communication Disorders*. https://doi.org/10.1016/j.jcomdis.2023.106381

Moreau, C. N., Joanisse, M. F., Mulgrew, J., & Batterink, L. J. (2022). No statistical learning advantage in children over adults: Evidence from behaviour and neural entrainment. *Developmental Cognitive Neuroscience, 57.* https://doi.org/10.1016/j.dcn.2022.101154

Parks, K., M.A., **Moreau, C. N.**, Hannah, K., Brainin, L., & Joanisse, M. (2021). The task matters: A scoping review on reading comprehension abilities in ADHD. *Journal of Attention Disorders, 26*(10), 1304-1324. DOI: 10.1177/10870547211068047

Articles Submitted

Moreau, C. N., Parks, K., Brainin, L., & Joanisse, M. F. A systematic review and meta-analysis of multimedia learning: Dual modality input improves second language learning.

Conference Presentations

Moreau, C., Brainin, L., & Joanisse, M. (2023). A systematic review of language and reading disorders. Poster presented at Psychonomics, San Francisco, USA.

Joanisse, M., **Moreau, C**. & Vanden Bosch der Nederlanden. (2022). Linking speech perception and phonology to reading disability via neural phase locking to speech. Oral presentation at Ensuring Full Literacy Annual Meeting, Toronto, ON.

Moreau, C. & Joanisse, M. (2022). Neural entrainment of natural language in a large-scale sample of school-aged children. Poster presented at Interdisciplinary Advances in Statistical Learning Conference, San Sebastian, Spain.

Moreau, C., Batterink, L. J., & Joanisse, M. F. (2020). Statistical language learning in children and adults is indexed by neural entrainment. Oral presentation at the Neuroscience Research Day, London, ON.

Moreau, C., Batterink, L. J., & Joanisse, M. F. (2019). Neural entrainment indexes statistical learning in children. Poster presented at the Psychonomic Society's annual meeting, Montréal, QC.

Moreau, C., Liesemer, K., Child, I., Joanisse, M. F., & Batterink, L. J. (2019). Statistical learning and how it relates to language and reading abilities: An EEG study. Poster presented at the Canadian Society for Brain, Behaviour and Cognitive Science, Waterloo, ON., *and* at the Developmental Disabilities Research Day, Western University, London, ON.

Moreau, C., Liesemer, K., Child, I., Batterink, L. J., & Joanisse, M. F. (2019). A look at statistical language learning and how it relates to the emergence of language and reading disorders. Data blitz (3-minute oral presentation) and poster presented at the Research Special Interest Group Research Day, Niagara Falls, ON.

Moreau, C., Joanisse, M. F., & Batterink, L. J. (2019). Statistical learning across visual and auditory modalities. Five-minute oral presentation and poster presented at Western Research Forum, Western University, London, ON., *and* poster presented at the Lake Ontario Visionary Establishment (LOVE) conference, Niagara Falls, ON.

Moreau, C. & Fennell, C. T. (2017). The effects of mobile media use on language acquisition in monolingual and bilingual infants. Poster presented at the International Symposium on Bilingualism (ISB11), University of Limerick, Limerick, Ireland.

Workshops Presented

Moreau, C. & Parks, K. (2022). An Introduction to Scoping Reviews, Systematic Reviews and Meta-Analysis. Coding Social. Western University, London, ON.

Vanden Bosch der Nederlanden, C. & **Moreau, C.** (2020). Neural Entrainment as an Index of Speech Processing in Language Learners. Workshop presented at the Ensuring Full Literacy SSHRC Partnership Grant monthly meeting.

Awards and Accolades

2022	**Richard A. Harshman Award** based on academic achievement, $1500
2021	**Career Profile Advisor of the Month**, Western Employment Resource Center, Western University
2021	**Top E-advisor**, Western Employment Resource Center, Western University
2021	**Certificate of Teaching Excellence**, The Canadian Council of Departments of Psychology, $50
2020	**Leola E. Neal Award** for the most outstanding Master's thesis, $500
2019	Ontario Association on Developmental Disabilities: Research Special Interest Group Student **Travel Award**, $150
2015-2016	**Dean's Honours List**, University of Ottawa
2011	**Admission Scholarship,** University of Ottawa, $500

Research Experience

2019	**Guest Peer Reviewer**, Developmental Science
2016-2017	**Research Assistant**, Cognitive Psychology of Language Laboratory University of Ottawa, ON Supervisor: Dr. Alain Desrochers
2015	**Research Assistant**, Social Psychology of Language and Communication Laboratory, University of Ottawa, ON Supervisor: Dr. Richard Clément

Teaching Experience

2017-2023	**Teaching Assistant,** Western University
2020	**Marker,** Western University
2018-2019	**Co-supervisor**, co-supervised two students for their undergraduate thesis, Western University
2018	**Summer Proctor**, Western University

Community Involvement

2020-2023	**Trainee committee member**, Ensuring Full Literacy SSHRC Partnership Grant Training Committee
2021-2022	**Career Profile Advisor**, Western Employment Resource Centre, Western University, London, ON

2019-2021	**Co-chair**, Psychology Colloquium Committee, Western University
2018-2020	**Co-chair**, Psychology Graduate Student Association (PGSA), Western University
2020	**Chair for Lightening Presentation**, Ensuring Full Literacy SSHRC Partnership Grant Annual meeting
2019	**Volunteer**, Psychonomic Society's 60th annual meeting, Montréal, QC
2019	**Psychology Representative**, Science Rendezvous, Western University
2019	**Graduate Student Representative**, Undergraduate Affairs Committee, Western University
2019, 2018	**Volunteer**, Canadian National Brain Bee, Western University
2018	**Volunteer**, Inspiring Young Women in STEM Conference, Western University
2018	**Volunteer Editor**, Western Undergraduate Psychology Journal, Western University

Certifications

2018	Teaching Assistant Training Program certificate, Western University, London, ON
2018	Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans Course on Research Ethics (TCPS 2: CORE), Western University, London, ON

Workshops Attended

2022	Career Preparation Series • Interview preparation • Expanding personal network • Identifying, assessing, and articulating the skills developed during the PhD and how to articulate them in academic/non-academic career settings.
2020	Data Visualizations, Society of Neuroscience Graduate Students, Western University
2020	How to Pitch a Great Story Idea, The Conversation Canada