Auditory Evoked Potentials as a Window into Word Learning in Dyslexia: Mismatch Negativity, Response Time and Accuracy, and Associated Language Deficits

by

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ABSTRACT

Objective: Previous studies have observed that adults with dyslexia display a reduced N1 gating when exposed to repetitive stimuli. Robust gating is associated with the ability to recognize familiar stimuli and identify the stimuli that will need novel memory representations formed. This study investigates if the mismatch negativity component in electroencephalographic-produced Event-Related Potentials (ERPs) is affected as well by diminished memory forming in adults with dyslexia. Additionally, signal/ noise processing for auditory-based memory recollection and thus word learning is explored.

Methods: Nineteen adults with dyslexia and 18 adult controls participated in a classic auditory oddball electroencephalographic experiment here referred to as DIFF, to indicate that the tones differed in frequency, while incorporating a decision-making task that signified participant tonal discrimination. Mismatch Negativity (MMN) amplitudes (AMPs) and latencies were collected from ERPs. Behavioral data consisting of reaction time (RT) and accuracy (ACC) of tone choice were documented.

Results: Group differences for accuracy and reaction time in the DIFF task were highly significant. The dyslexic group produced longer reaction times and with less accuracy than the control group. The Mismatch Negativity amplitude and latency collected did not differ significantly between groups, however, correlations to other variables obtained from similar studies consisting of the same participant group were observed. Linear regression models indicated predictions for accuracy and reaction time results based upon WID scores (Word Identification Test) and SWE scores (Sight Word Efficiency) respectfully.

Conclusions: Neural processing speed and the ability to form permanent memory representations of auditory sound bites for retrieval is dampened in dyslexic populations.

Significance: To better illuminate and understand the neural mechanisms of dyslexia, specifically auditory processing, with the goal of improving outcomes in individuals with dyslexia through more efficient therapy treatment options.

DEDICATION

1. Thank you to my friends and family who supported and encouraged me throughout the entirety of this research project.
2. To my children, Ari, Layla, and Kansas, who give me my purpose; your unrelenting belief in my ability to succeed, even when I had doubts in myself, kept me going when I couldn't find the strength within. Let this accomplishment always be a reminder to you three that no matter the obstacles, you can achieve anything your heart desires with hard work and perseverance!

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

INTRODUCTION

Overview

The neural capacity of the brain in processing auditory stimuli is diverse in nature. The term neurotypical is used in research-related avenues to describe a standard norm of a functional brain. In all reality however, there is no perfect mold to compare all others to. The functional ability of each brain is vastly different, which also stands true for those not deemed neurotypical. Dyslexia is not able to be characterized by one singular or identical deficit. In fact, dyslexic individuals can manifest symptoms of the disorder in a large magnitude of phenotypic expressions. At the present time, a biological test that definitively diagnoses an individual with dyslexia is crushingly absent. However, what clinicians and language pathologists do use, are various tests and observable tasks that have shown to elucidate the underlying disorder.

The way in which dyslexia physically manifests is a window into how the neural processing of stimuli is conducted. The American Psychiatric Association describes dyslexia as being, "a specific learning disorder with impairment in reading and is characterized by problems with accurate or fluent word recognition, poor decoding, and poor spelling abilities" (2013). These impairments are not the disease itself however, but rather, the physical manifestations of the dysfunctional dyslexic neural processing system. One purpose of this study is to investigate if a common neural deficit can be identified using electroencephalographic (EEG) modalities as well as to decipher how the observed neural deficits can predict observable outcomes.

Review of Literature

Phonological Impairments

Dyslexia is commonly associated with reading and language impairments, but what does that exactly mean? Phonological impairments, or the increased difficulty in manipulating the basic sounds of spoken language is a commonly used attribute for dyslexia. Learning the skills required for language development is essential for elementary-aged children. Skills such as the memorization of letter sounds, combinations of sounds and the ability to decode unfamiliar words, commonplace to neurotypical children, can become the reason dyslexic children so often fall behind. Studies have shown through diagnostic reading-related measures, those with dyslexia produce significantly lower scores when compared to neurotypicals. These results were true for both speech and nonspeech examinations (Gabay et al., 2015). Phonological impairments at this stage of development lead to language and reading difficulties that can take years or even a lifetime to overcome (Tallal & Gaab, 2006).

Neural Processing of Auditory Stimuli

An important question to ask is what aspect of phonemic learning is impaired in dyslexia? Studies have shown that the impairment can be first observed during the initial introduction of the stimuli. Using ERP modalities, irregularities attributed to processing acoustic information necessary for speech perception have been observed. In addition to speech, non-speech sounds also were found to elicit atypical ERP waveforms when compared to neurotypicals (Schulte-Körne & Bruder, 2010).

Deficient Neural Adaptation and its Role in Memory Formation

The result of diminished neural adaptation and perception impairment is inefficient memory formation. This deficit is often associated with the reason afflicted children demonstrate an inefficiency in learning the basic principles of language, i.e. – phonemes and linguistics. Prior research has observed immediate dysfunctional adaptation to different stimuli such as spoken words and visual objects (Perrachione et al., 2016). Other studies have observed an increased rate of memory decay in dyslexic populations when compared to neurotypicals (Jaffe-Dax et al., 2017). This often leads to less precise neural representations of phonological components, resulting in language deficits during adolescence. In another ERP study, N1 Gating Magnitude was investigated to better understand how auditory processing differs from controls (Peter et al., 2019). In this study, the N100 exogenous sensory ERP component was investigated. The N100, is a response-related refractory ERP component, that when presented with two identical stimuli, diminishes in amplitude or electrical potential upon the presentation of the second stimuli (Näätänen et al., 2007). Using repetitive nonword tones as stimuli, the dyslexic participants displayed a diminished neural adaptation, which was in contradiction to the controls. These results provided evidence that dyslexic neural processing mechanisms lack the ability to adapt to repetitive stimuli with the same proficiency as controls (Peter et al., 2019).

Statement of the Problem

The neural dysfunctions present in dyslexia are multifactorial. Phonological processing impairments, commonly associated with dyslexia, makes it difficult for individuals with dyslexia to process the acoustic information contained in formants, or frequency peaks associated with the difference resonance levels produced for each letter, and sounds of language. This becomes a hindrance especially to children and young adolescents who are still learning the basic laws of phonemes, letters, and words. Impairments have also been observed while decoding nonword and general acoustic information-processing tasks. To address the deficits efficiently, a clear understanding of the neural underlying processes that cause the dysfunction is of paramount importance. The use of ERP studies to address the undefined atypical neural aspects of dyslexia is beneficial in that they produce an accurate representation of the deficits at the electrical impulse level of perception. The DIFF experiment, aimed to analyze frequency discrimination, memory, and subsequent extraction, is unique in that it incorporates a large magnitude of data in which to compare, correlate and further investigate upon, resulting in a larger scope of possible inferences.

Hypotheses

This research experiment investigates how dyslexia's neural processing mechanisms differ from neurotypicals by reporting behavioral and ERP data produced by dyslexic and control adults during a classic auditory oddball EEG paradigm. A behavioral response measured efficiency in decision-making, based upon auditory memory representations. The research questions, hypotheses and predictions explored in this study are the following:

1. Do participants with dyslexia perform with lower accuracy on the DIFF task, compared to typical controls? I hypothesize that the ability to form

immediate memory representations of auditory stimuli is associated with the reduced neural gating observed in the N1 Gating study (Peter et al., 2019). Further investigation upon the association between reduced N1 Gating Magnitude and accuracy scores in the DIFF task will be needed to correlate the two. I predict that the dyslexic participant group will produce a less accurate mean score when compared to the neurotypical group (prediction 1).

2. Do participants with dyslexia perform with longer reaction times on the DIFF task, compared to typical controls? I hypothesize that the general neural processing deficit commonly associated with dyslexia (Peterson and Pennington, 2015) will be observed behaviorally with longer response times in the dyslexic participant group, compared to the typical controls (hypothesis 2a). - I further hypothesize that a delayed or longer response time is associated with an impaired auditory memory representation production and retrieval circuit, or what is commonly referred to as the Rapid Auditory Processing Deficit Hypothesis (Tallal & Gaab, 2006) (hypothesis 2b). I predict that the dyslexia group will demonstrate longer reaction times when compared to the control group (prediction 2).

3. Will the dyslexia participants produce a diminished MMN compared to neurotypicals? I hypothesize that the neural processing deficit associated with dyslexia, defined by accurately perceiving, processing, storing, and retrieving auditory information (Schulte-Körne and Bruder, 2010), will be substantiated by the evoked ERP waveforms that will demonstrate less reactivity, compared to neurotypicals, when confronted with the odd-toned

stimuli. I predict that the dyslexia group will produce Mismatched Negativity Difference waves that are dampened in contrast to the neurotypical ERP waves (prediction 3).

4. What is the connection between the brain's response and the accuracy of participant tonal choice accuracy? I hypothesize that a larger MMN amplitude will signify an effective neural auditory processing system (hypothesis 4a). It is commonly known from research that the MMN ERP component is elicited when an irregularity is detected amongst standard auditory stimuli (Paavilainen, 2013). Thus, the intensity of the brain's reaction to the stimuli, will signify the perceived strength of distinction between the two tones. I hypothesize that a stronger distinction will correlate to each participant's accuracy level score, achieved with proper tone choices (hypothesis 4b). In simplest terms, the more distinct each tone is to a participant (elicited by the MMN), the higher the probability the participant, using their memory representations of each tone, will choose the correct tone (based upon individual's rapid neural adaptation to the tonal stimuli). I predict that a correlation will be observed between higher accuracy scores and MMN amplitudes (prediction 4a). I predict that participants with larger MMN's will also produce faster response times (prediction 4b).

5. What other variable used in this study will be the strongest predictor of accuracy in the dyslexic population during the DIFF task? The ability to form permanent memory representations of auditory stimuli coupled with a

functioning and rapid retrieval of said information, will be pertinent in achieving proficient accuracy scores. A MMN study conducted in 2006, concluded that pitch discrimination is impaired in dyslexic cases (Kujala et al., 2006). Thus, the initial auditory processing of the DIFF task tones to form distinct memory representations of each, would already be inconsistent or imprecise in the dyslexic cases. Knowing this, I hypothesize that the WID (Word Identification Test) will be an effective predictor for accuracy scores. The WID, a preliminary exclusionary requirement for this experiment, assessed the participant's ability to accurately read sight words. Both the WID and DIFF task accuracy scores rely on the effective production and implementation of stable neural representations of stimuli (auditory and phonological). Thus, I predict that a participant's WID score will most predict their DIFF task accuracy score (prediction 5).

6. What other variable used in this study will be the strongest predictor for reaction time in dyslexic populations during the DIFF task? I hypothesize that the participant's ability to rapidly react to a stimulus and subsequently, respond with their tone choice via the tap of a key, will be correlated with their base digital tapping speed potential. The tapping test measured the average reaction time between the onset stimulus and the 1st key tap. This is effectively a measure of how fast the participant responded to the stimuli, signified by a finger tap of the chosen button. The reaction time scores in the DIFF task were dependent upon the base response time potential retrieved by the tapping test, integrated with the executive functioning

cognitive task which involved tonal discrimination for each stimulus presented. Thus, I predict that the finger tapping test will be the most effective predictor for reaction times in the DIFF task (prediction 6).

METHODS

Participants

This study was approved by the Internal Review Board at the University of Washington, obtained on its own behalf as well as on behalf of Arizona State University. All participants gave their written consent to be included in the experiment, prior to their involvement.

In sum, there were 42 adult participants in this study. Twenty of these participants were controls, whereas the other 22 were adults with dyslexia. Thirty-seven of these adults successfully completed the DIFF experiment. The DIFF participants consisted of nineteen dyslexic adults, twelve of which were females and seven that were males. The mean age ($M_{age)}$ = 407.63 months or 33.97 years old. The standard deviation of age range ($SD_{age)}$ = 161.48 months or 13.46 years. The age range was from 215 – 686 months or 17.9 – 57.2 years. The control group consisted of ten females and eight males for a total of eighteen participants. The control group's M_{age} = 329.78 months or 27.48 years with a SD_{age} = 145.98 months or 12.17 years. The ages ranged from 205 – 619 months or 17.1 – 51.6 years (

Table *1*).

Table 1 Group Means, Standard Deviations, T-Test Statistics, & Significance Values for Sex, Affected Status, & Age for All Participants in the Study

Demographics				
	MEAN	SD	t	p
Sex	1.57	0.501	20.33	<.001
Affected	1.52	0.505	19.54	<.001
Age (years)	33.57	15.76	13.81	<.001

*1 = male / 2 = female   *1 = control / 2 = dyslexia

Of these 37 total participants, 25 produced ERP data used to calculate MMN difference waves. There were 16 control participants, 9 were female and 7 that were male. The M_{age} = 317.69 months or 26.47 years and the SD_{age} = 134.94 months or 11.25 years. The ages ranged from 205 – 619 months or 17.1 – 51.6 years. The dyslexic group consisted of 7 females and 2 males for a total of 9 participants. The M_{age} = 349.67 months or 29.14 years and the SD_{age} = 104.27 months or 8.69 years. The age range was 230 – 534 months or 19.2 – 44.5 years (Table *2*). The participant groups were not exactly evenly distributed, thus, the differences were found to be significant (Table *1*).

Table 2 Demographic Data Statistics for Participants in the DIFF and MMN Experiments Respectively (units in years)

VARIABLE	BEHAVIORAL		MMN	
	CONTROL (10F / 8M)	DYSLEXIC (12F / 7M)	CONTROL (9F / 7M)	DYSLEXIC (7F / 2M)
Mage	27.48	33.97	26.47	35.47
SDage	12.17	13.46	11.25	16.39
Range	17-51	17-57	17-51	19-70

A passing result on a hearing screen was required for all participants at 20 dB HL for 05, 1, 2, and 4 kHz. The participants were required to be free of any comorbidity or disorder that could introduce any confounds into the data. The control group completed five preliminary tests (four reading and one spelling further described below) and were admitted to the study with scores above -1 standard deviation on all five tests (Peter et al., 2019). The control participants had never been diagnosed with any form of dyslexia. The dyslexic group consisted of participants who had been formally diagnosed with dyslexia. The dyslexic participants, upon the completion of the reading and spelling tests, were admitted to the study with scores below one standard deviation of the mean in at least one of the five tests. Additionally, the Reynolds Intellectual Assessment Scales (RIAS) test was administered to each participant. This test has a verbal and nonverbal IQ subscale. All participants were required to have nonverbal composite scores above –1 SD but only the typical controls were required to have verbal composite scores above –1 SD since individuals with dyslexia have deficits in spoken language. Controlling for nonverbal IQ in the typical range was done to ensure that the participants were free of intellectual disabilities, thus minimizing confounds from that source.

Procedures

Confirmatory Participant Tests

Potential participants completed four reading and one spelling test prior to enrollment. Inclusionary boundaries described above were implemented using the participant's scores. The Word Identification (WID) and the Nonword Decoding

(WATT) subtests were both untimed tests that measured sight word reading abilities and the participant's ability to decode nonwords, respectively (Woodcock et al., 2001). There were also two, timed reading tests consisting of the Sight Word Efficiency subtest (SWE) and the Phonemic Decoding Efficiency subtest (PDE). These measured the participant's ability to sight read words and decode nonwords (Torgesen & Rashotte CA, Wagner RK, 2012). The last subtest was from the Wechsler Individual Achievement Test - II (WIAT II) (Wechsler, 2005) and measured the participant's spelling ability. The purpose of these tests was to assure that participants were well suited for each group, thus, its of no surprise that there were significant mean differences between the groups for each of the tests. The dyslexia group produced significantly lower scores when compared to the control group. Table *3* summarizes the results obtained from these five exclusionary tests.

Table 3 Exclusionary Reading and Spelling Tests for All Participants (left panel) and Participants Who Provided MMN Data (right panel)

VARIABLE	BEHAVIORAL				MMN				t	2-Tailed p	Cohn's d
	CONTROL		DYSLEXIA		CONTROL		DYSLEXIA				
	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD			
WIAT	112	9.89	90.53	15.19	106.25	13.17	89.11	17.59	5.41	<.001	1.67
SWE	100.56	4.46	83.84	15.67	94.06	17.07	84.33	14.12	4.18	<.001	1.29
PDE	98.61	9	77.37	7.4	92.38	12.27	75.89	8.48	7.94	<.001	2.45
WID	105.83	7.21	93.37	7.61	103.69	8.76	90.78	8.87	5.57	<.001	1.72
WATT	104.5	10.43	94.05	8.17	100.44	9.06	94.56	10.96	3.6	<.001	1.11

Electroencephalographic Recording

Each participant was positioned in a quiet room inside a university research lab. They were positioned sitting in a chair facing a computer screen that displayed a crosshair image. The participant was instructed to focus on that image during the testing. A 128-electrode net was fitted on their scalp and a continuous EEG recording was initiated using the Net Station 2.0 program. Data was collected via a high-density recording system (Electrical Geodesics Incorporated, Eugene, OR) using the vertex electrode as reference. The auditory stimuli presented to the participants was via inserted earbuds with the program E-Prime 2.0. The recordings were approximately 10 minutes in length prior to filtering. The odd tone (1025Hz) played 20% of the time and the common tone (1000Hz) played the other 80%. Each participant completed 250 trials consisting of 25 cycles of ten presented auditory tone stimuli. Each trial was varied in odd and common tone presentation order while confirming that an odd tone onset never preceded another odd tone.

Auditory Stimuli and Tone Identification

Prior to the initiation of the recording, each participant was exposed to each of the two tones so to form a memory representation of each. During the recording, the participants were instructed to push one of two buttons with their finger dependent upon which tone they perceived to have been played. The choice made as well as the time in which it took the participant to decide and push the button were recorded for analysis. A practice run was completed by each participant to ensure that the participants understood the task as well as to insure they could perceive a difference between the two tones.

Additional Data Sets

For evaluation and comparative purposes, datasets from other previously completed experiments were included in the data analysis of this project. The participants who participated in the following experiments were the same group as the DIFF task experiment. The first included was from a word pair task in which the participant was presented with a pair of words. These words could be the same or different. The participant was tasked with pressing one of two keyboard numbers depending upon their choice of same or different. The accuracy and reaction times were recorded and used for this study (Table 6).

Statistical data retrieved from the Reynolds Intellectual Assessment Scales (RIAS) tests was also used for comparison measures for this study. The RIAS measures static verbal knowledge which relates to the ability to form permanent word representations and recall them efficiently (Table 6).

Data sets from four other speed tasks were also used. The first was a finger tapping test which measured how fast the participant was able to tap one key with one finger given a timeframe. The second consisted of the participant repetitively repeating, “papapapa” as fast as they could. Their individual syllable duration rates were also recorded and converted to Z scores (based on norms set by Fletcher et al., 1994) used for this study. The last two consisted of a monosyllabic and disyllabic repetitive motion test that recorded that rate in which each person completed the task. The last data set used was from the previously mentioned N1 Gating Magnitude experiment (Peter et al., 2019) (Table 6).

Table 4 Supplementary Data Set Statistics: Means, SD, p, & t – Test Statistics

VARIABLE	MEAN		SD		p	t
	CONTROL	DYSLEXIA	CONTROL	DYSLEXIA		
WORD PAIR RT (ms)	968.87	1241.04	171.77	282.18	<.001	-3.73
WORD PAIR ACC (logit)	2.85	2.36	0.43	0.53	0.001	3.26
RIAS (SS)	115.37	112.81	10.93	8.76	0.208	0.821
FINGER TAPPING (ms)	393.94	435.11	79.27	73.72	0.044	-1.74
PAPAPA Z SCORE (SS)	1.1	0.32	1.12	0.79	0.006	2.64
MONOSYLL Z SCORE (SS)	0.93	0.28	0.55	0.88	0.003	2.85
DISYLL Z SCORE (SS)	0.54	-0.31	0.74	1.13	0.004	2.82

N1 GATING MAGNITUDE (%)	0.45	0.2	0.22	0.25	0.005	2.75

RESULTS

Data Acquisition

All preprocessing of the collected EEG raw data was conducted through MatLab (R2021a) on the EEGLAB extension program version 2021.1. Each file was processed using the same steps and requirements. Each raw file's frequency pass band was filtered with an upper and lower edge limit of .5-50Hz. The data was re-referenced to the channels 57 and 100, which were the average of the mastoids. The samples were reduced to a sampling rate of 500Hz except for 3 of the first participants whose data was already collected at a 250Hz sampling rate. The reject data using Clean Rawdata and ASR tool was employed and the number of channels removed was noted. The odd and common toned-associated epochs were then extracted using an epoch limit of .5 – 1.5 seconds. The baseline latency range was set to a min of -100 and a max of zero.

The subsequent ERPs that were produced via the process described above, were then analyzed to locate the neural component that was elicited by each of the common and odd tone auditory stimuli. The odd tone-produced ERP was used to isolate the amplitude and latency in which the intended neural reaction occurred. That specific odd latency was then used with the common tone-produced ERP to locate the corresponding amplitude of the participant's neural response. The difference between the two amplitudes was found and recorded as the MMN (

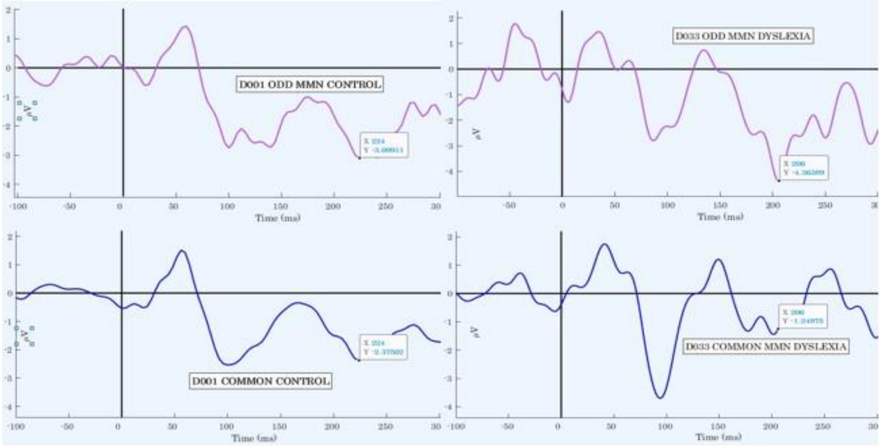

Figure 1). As per Steven Luck's ERP component standards (2014), the mismatch negativity (MMN) peaks between 160-220ms after stimulus onset. The MMN neural response occurs in response to an auditory stimulus that is slightly varied from the stimuli that shortly preceded it. Through Luck and other published work, it is assumed that the MMN component summates maximally on the scalp in the fronto-central region. Thus, nineteen electrodes were chosen for ERP component analysis. These electrode locations are the following (EGI electrode system): E55 (Cpz), E31. E80, E30 (C1), E7, E106, E105 (C2), E13 (FC1), E6 (Fcz), E112 (FC2), E12, E5, E11 (Fz), E20, E118, E19 (F1), E4 (F2), E29 (FC3), and E111 (FC4).

Data Reduction

The data provided for the behavioral DIFF task was produced by several reduction methods. Any reaction time marked as a zero was first removed as those were either faulty data points or prior to the initiation of the experiment. The two highest and lowest times recorded were then removed to account for any outliers that could skew the data. The means were then calculated for each participant and recorded. The accuracy data was treated in the same function as the reaction time data. The mean accuracy scores for each participant were then transformed into a proportion ranging from 0-1 (0 = every tone was incorrectly identified, 1 = every tone was correctly identified). This new data set, referred to as P, was again transformed into a designated P1 value using the formula, (P*.95) + .025. This allowed the data to be rescaled to range from .025 - .975. Lastly, the logit or natural log was calculated (P2) using the formula, log(P1/(1-P1)). The resulting P2 was then used for further analysis as the accuracy score for the DIFF task experiment. The other data sets used for analysis purposes were reduced by similar means in previous studies. The MMN waveforms were created using EEGLAB utilizing the channel ERP image option with the nineteen previously denoted channels and using all other automatic options. The graphs were produced in SPSS using the chart builder option.

Statistical Procedures

For the analysis portion of the project, IBM SPSS statistical software was used. The means, standard deviations (SD), significance (p), t-test statistic and Cohn's d (effect size) were found using SPSS analysis tests. Independent samples t-tests were used to analyze group differences. For correlational analysis statistics, Pearson Correlations under Bayesian Statistics were used to produce the Pearson Correlation Coefficients. The linear regression models were produced using SPSS as well and incorporated dummy control and affected variables as selection categories for the individual population models.

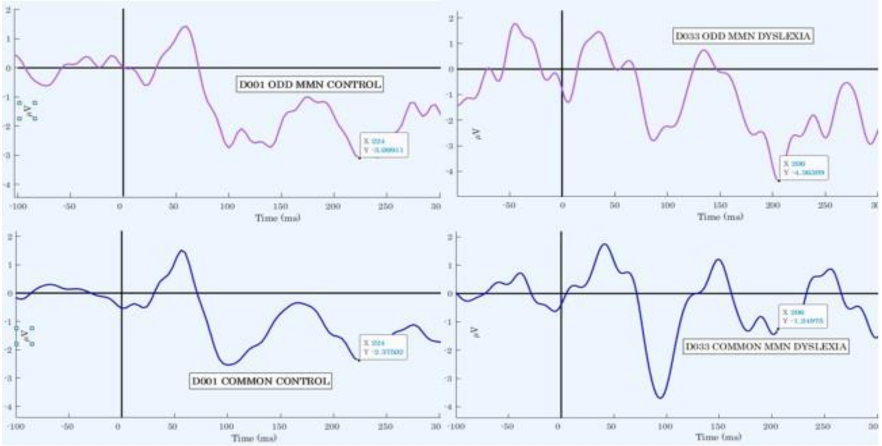

Figure 1 MMN ERPs Showing Both Common and Odd Neural Response Waves from a Control (D001) and Dyslexic (D033) Participant

Table 5 Overview of Statistical Tests

OVERVIEW OF STATISTICAL TESTS

TEST	GROUPS	PREDICTION	VARIABLES	BONFERRONI ALPHA
T tests for group differences between CTR and DYX groups	DYX vs. CTR	1	DIFF ACC	0.05
		2	DIFF RT	0.05
		3	MMN AMP	0.05
Pearson Correlation		4a	DIFF ACC & MMN AMP	0.025
		4b	MMN AMP DIFF RT	0.025
Linear Regression Models	DYX, CTR, & Both	5	DIFF ACC, WID, MMN AMP, GM, RIAS	0.0125
		6	DIFF RT, SWE, Mono, Tap, GM	0.0125

CTR = Control, DYX = Dyslexia, ACC = accuracy, RT = reaction time, AMP = amplitude, GM = gating magnitude, Mono = monosyllabic Z scores, Tap = finger tapping test, WID = word identification test, SWE = sight word efficiency test

Behavioral Accuracy and Reaction Time

After evaluating the behavioral data for each of the diff task components (accuracy and reaction time), the results showed that dyslexic participants displayed lower mean accuracy scores as well as longer mean reaction times (Table *7*). The figure below demonstrates the significant mean difference between the groups for accuracy in tone choice (p = <.001). When comparing accuracy scores for each of the groups, not only is there a significant mean, but the range at which dyslexic participants scored was also larger. The control group displayed a tightly bound accuracy zone with a mean value of 2.924. The dyslexic group had a mean of 1.555 and the scope of accuracy scores was increasingly broader.

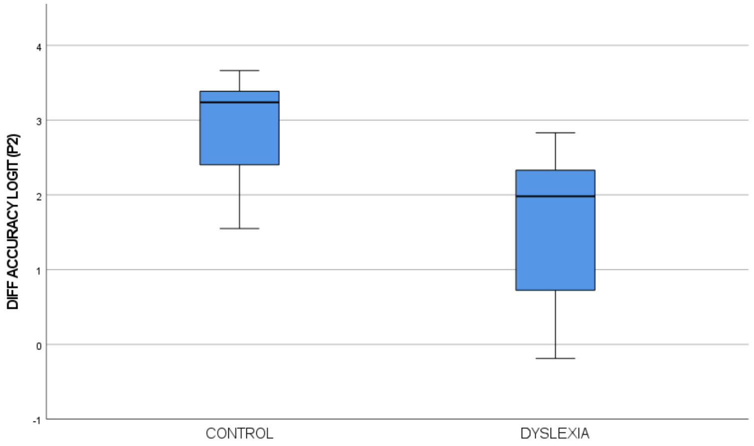

Figure 2 Accuracy scores (logit) of each group in the DIFF task experiment

The group difference for reaction times were also significant with a p value of .021 (Table 6). There were two outliers observed for the control group (D032 and D004). The means for each participant group, shown in Table *7*, were statistically significant in their variance (609.52 ms control vs 721.52 ms dyslexia). The range for each demographic was also significant where the control group's range of reaction times were bunched closely together. The dyslexia group's results varied more drastically with a broader range of times compared to the typical results (Figure *3*).

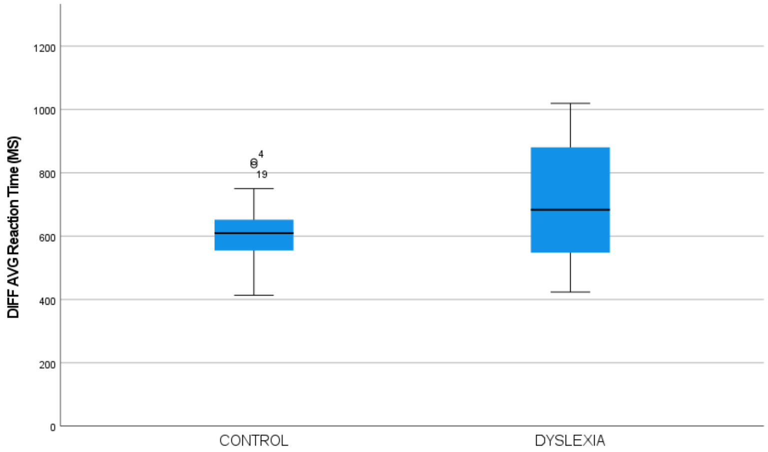

Figure 3 Reaction Time Values in the DIFF Task Experiment for Each Group

Electroencephalographic Results

The Mismatch Negativity amplitudes and latencies were extracted from processed ERP waves produced using the EEGLAB protocol. The control group's mean difference wave amplitude was 1.943 μV with a standard deviation of 2.11 whereas the dyslexia group was 1.728 μV with a SD of 1.03 (Table 7). This data was not statistically significant (p = .139) and as Figure 4 depicts, the results showed minimal difference between both groups.

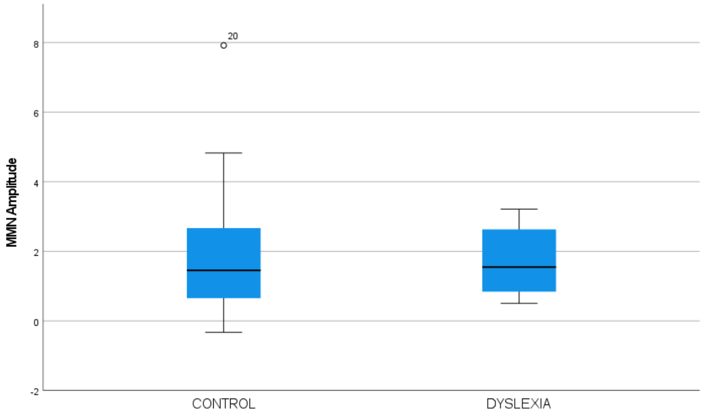

Figure 4 Mismatch Negativity Difference Wave Amplitude Results for Both Control and Dyslexia Groups

The MMN latency results were slightly more varied between the experimental groups than the amplitudes. The mean latency for the control group was 197.63 ms with a standard deviation of 54.65. The mean latency for the dyslexia group was slightly earlier at 189.27 ms with a standard deviation of 37.10 (Table 7). The range of latencies observed is worth noting in that the control group produced a broader scope of times versus the dyslexia group (Figure 5). Conducting an independent samples test of both data sets (Table 6) found that neither component was significant with p values of .139 (amplitude) and .055 (latency).

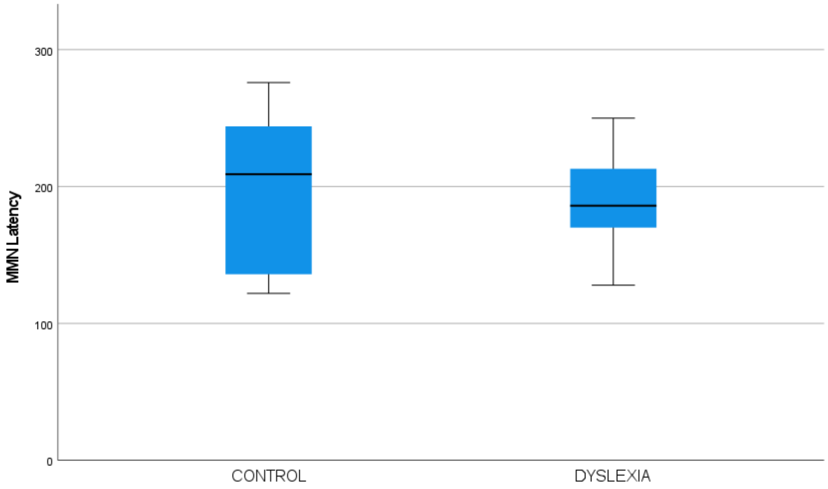

Figure 5 Mismatch Negativity Latency Results for the Affected (Dyslexia) Group

Table 6 Independent Samples T Test Results for the DIFF and MMN Experiments: t, p, and Cohen's d

Independent Samples T Tests			
(Equal Variances Assumed)	t	p	Cohen's d
MMN AMP (μV)	0.31	0.14	0.122
MMN Latency (ms)	0.44	0.06	0.173
DIFF AVG RT (ms)	2.1	0.02	-0.692
DIFF ACC (logit)	4.75	<.001	1.561

Table 7 Means & SDs for MMN and DIFF Experiments

(Equal Variances Assumed)	MEAN		SD	
	CONTROL	DYSLEXIA	CONTROL	DYSLEXIA
MMN AMP (μv)	1.94	1.73	2.11	1.03
MMN Latency (ms)	197.63	189.27	54.65	37.1
DIFF AVG RT (ms)	609.53	721.52	117.93	194.58
DIFF ACC (logit)	2.92	1.55	0.69	1.02

Correlation Findings

Further statistical analysis was conducted to investigate the correlation levels between the MMN amplitude and latency, the DIFF task amplitude and accuracy, and the N1 Gating Magnitude data set (Peter et al., 2019). The correlation scatter plots below, were done for both control and dyslexia groups separately (Figure 6). The correlation between the MMN Latency and the N1 Gating Magnitude for each demographic is worth noting. The dyslexic population produced a sharp upward linear correlation to the N1 Gating Magnitude data. The control group in contrast displayed a slightly negative linear association. Additionally, there are contrasting results involving the correlation between DIFF accuracy and the MMN latency (Figure 6). These observable correlations are further investigated with linear regression models described in the subsequent section.

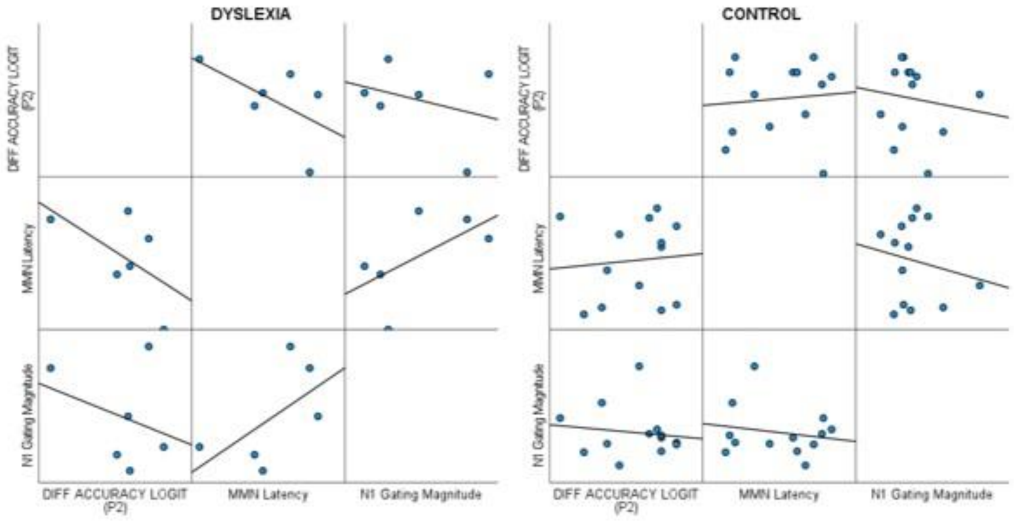

Figure 6 Correlation Scatter Plots for MMN Latency, DIFF ACC and Gating Magnitude

Linear Regression Models

To determine if there were any predicting factors for the DIFF experiment variables, reaction time and accuracy, six linear regression models were computed below.

DIFF Task Accuracy Models

The first model was built only using the control subjects with available corresponding variable data (N = 13). The dependent variable used was accuracy scores for the DIFF task. The independent variables were Gating Magnitude, RIAS scores, MMN amplitude, and the WID. The second model was framed the same but excluded the control participants (N = 6). The third model used both neurotypical and dyslexic data with the same approach (N = 19). Using a 1-tailed significance, no included variable was determined to be significant in the control regression model. The WID was observed to be significant for the dyslexic model (p = .012) and the combined model (p = .004) (Table *8*).

To design a hierarchical linear regression model, Pearson Correlation Coefficients were first obtained (Table *8*). Based upon those results, The first tested predictor was the WID, followed by the MMN amplitude, the N1 gating magnitude and lastly the RIAS scores.

Table *8* displays the independent variable coefficients produced with all four independent variables. This investigation did not result in any statistically significant predicting variables for DIFF accuracy. However, model two, which only used the WID scores and the MMN amplitude data, produced independent variables that are statistically significant and thus, are effective predictors for the dependent variable, DIFF accuracy, F(2, 16) = 6.558, p < .004.

Table 8 Hierarchical Multiple Regression (Based Upon Pearson Correlation Coefficient) Predicting DIFF Tone Identification Accuracy Outcomes for the Combined Model (N = 19)

Variable N = 19	B	SE B	ß	p	% R^2 Change	Pearson Coefficient
WID	0.069	0.02	0.781	0.004	0.316	0.562
MMN AMP	0.154	0.078	0.364	0.067	0.135	0.365
GATING MAGNITUDE	-0.062	0.583	-0.02	0.917	0.002	0.188
RIAS	-0.037	0.022	-0.375	0.117	0.091	0.067

DIFF Task Reaction Time Models

Three similarly structured linear regression models were also produced with reaction time as the target variable. The predictor variables chosen to investigate were the finger tapping test, the monosyllable Z score, N1 gating magnitude, the RIAS and the SWE reading test. Using a 1-tailed significance level for each model, no variables were found to be significant within the control group. However, within the dyslexia model, the variables monosyllable Z scores (p = .038) and SWE scores (p = .029) were found to be significant. The combined linear regression model produced two significant predictors as well which is to include SWE scores (p = .003), and Monosyllable Z scores (p = .007). A correlational scatter plot depicting the relationship between the SWE scores and the DIFF task reaction times is included in Figure *8*.

To design a hierarchical linear regression model like the previous accuracy models, Pearson Correlation Coefficients were first obtained. The regression models were then built in 4 levels, adding one independent variable to each level from the strongest correlated variable to the weakest in the following order: SWE, monosyll, tapping, and gating magnitude. The coefficients produced can be seen in Table 9. The two independent variables that statistically significantly predict the dependent variable (reaction time) in this regression model are SWE scores and the monosyllabic Z scores. Using the coefficients, the regression equation that follows model two with only using the two significant predicting variables is, F(2, 22) = 6.466, p = .006 where α = (.05/2 test variables) .025.

Table 9 Hierarchical Multiple Regression (Based Upon Pearson Correlation Coefficient) Predicting DIFF Tone Identification Reaction Times Outcomes for the Combined Model (N = 25)

Variable N = 25	B	SE B	β	p	% R^2 Change	Pearson Coefficient
SWE	-4.55	2.08	-0.44	0.003	0.284	-0.533
MONOSYLL Z SCORE	-63.38	38	-0.3	0.007	0.086	-0.485
FINGER TAPPING	-0.07	0.39	-0.04	0.223	0.005	0.159
GATING MAGNITUDE	72.13	116.15	0.12	0.459	0.012	0.022

DISCUSSION

The experimental results describing less accurate mean scores in the dyslexia group, support the predicted outcome for the first hypothesis. It demonstrates that correct responses in the DIFF task require accurate auditory stimuli processing abilities that are not associated with dyslexic populations (Ahissar, 2007). The predicted outcome of the affected group producing less accurate scores, was also supported with the observed results.

The DIFF task reaction time results demonstrate substantiating evidence for the predicted outcome that states the dyslexia group would produce longer reaction times when compared to the neurotypical values. This supports previous data stating there is a general neural processing deficit commonly associated with dyslexia, particularly with auditory stimuli in this case (Peterson & Pennington, 2015). Secondly, The Rapid Auditory Processing Deficit Hypothesis (Tallal & Gaab, 2006) which poses an association for dyslexic cases with a hindered ability to rapidly process auditory cues and information, is further substantiated with the DIFF task results. The dyslexic cohort for this experiment produced longer reaction times to the stimuli when compared to the controls which demonstrates how this group required an elongated time window to process the presented auditory information.

There were little observed differences in MMN amplitude between the two participant groups. Previously published literature has observed attenuated MMN amplitudes when compared to neurotypical populations (Kujala et al., 2006). This absent concept in this experiment would suggest that the dyslexia participants were less able to distinguish a difference between the two tones (1000 Hz and 1025 Hz) at the neural processing level. An expected attenuated MMN would have demonstrated the lack of distinguishment between the two tones, resulting in less neural reactivity to the odd tone, which would typically cause a larger deviance from the normal neural response. Such studies have also found that dyslexic cases, contrary to neurotypicals, evoked normal N1 component latencies (stimuli detector impulses) followed by prolonged MMN latencies (Baldeweg et al., 1999). The results in this experiment, contrasted with those findings. The results here could be due to the small population size as well as only producing one run for each participant denoting the same tonal frequency as odd for everyone. A second trial, in which the odd and common tones were switched, allowing for an increase in the number of trials and data points to use during preprocessing measures, could increase the results' statistical significance and produce more reliable data.

As for research question number four, pertaining to the relationship between the MMN amplitude and the DIFF accuracy scores, there is a larger positive correlation seen in the controls than in the dyslexia group. This supports the hypothesis stating an increased MMN amplitude signifies a greater perceived disparity between the two tones resulting in higher DIFF accuracy scores. These results support previous findings which observed general acoustic information processing deficits in dyslexia with irregular ERP findings (Schulte-Körne & Bruder, 2010). Upon completion of a Pearson Correlation analysis however, the correlation was not found to be significant ($p = .211$) even though the correlation coefficient was moderate with a value of .259. Given the constraints of the available data, a larger N may be needed to reveal the hypothesized pattern.

The results of the DIFF task accuracy models support hypothesis five stating the WID test, which assesses the participant's ability to read sight words efficiently would be the strongest predictor to DIFF accuracy. Figure *7* illustrates the observed linear relationship between the two variables with a positive slope of 3.16. This positive correlation, along with the p value (.004), provides evidence that the efficiency in which a participant can form, retain, and recollect phonological working memory information, influences an increase in efficiently completing the same processes with short-term auditory representations as well. For dyslexia especially, impairments in this process, signified by lower WID scores, moderately predicted decreased accuracy outcomes in the DIFF task. Impairments related to the dynamics of perception, could be the underlying mechanism causing this correlation. In another study, perceptual impairments were linked to deficits in phonological working memory and short-term memory (Ahissar, 2007). This association between the WID and the DIFF ACC results, further substantiates the studies' findings on perceptual impairments in dyslexia.

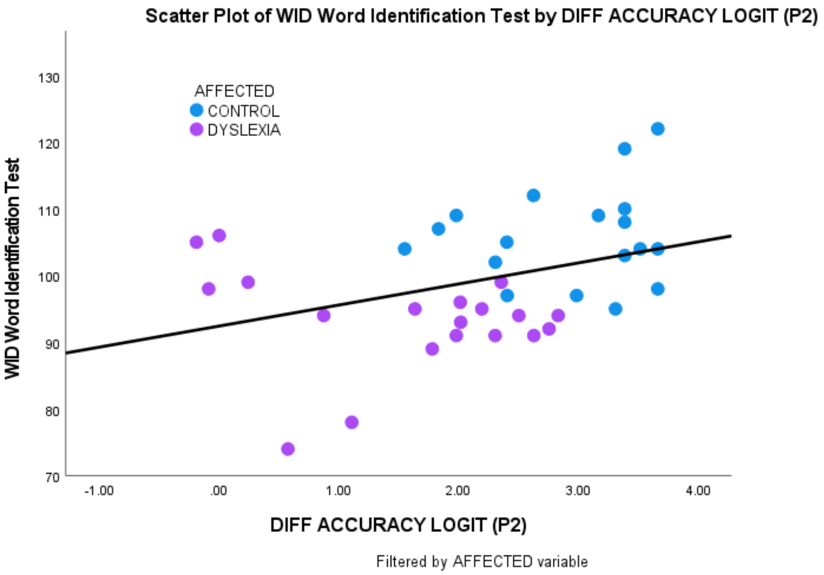

Figure 7 Scatter Plot Displaying Relationship Between DIFF Accuracy and the WID Scores Using the Combined Linear Regression Model for Data

The DIFF task reaction time linear regression model results did not support my 6th hypothesis in predicting that the tapping test would be the most influential predictor. The participant's ability to react to a stimulus with a finger tapping response only produced a significance value of $p = .223$ for the combined model, $p = .210$ for the control model and $p = .156$ for the dyslexia model. The measure that was the most influential predictor in the combined model, SWE scores, measured sight word efficiency and was timed. The reasoning for this could be related to the timed aspect of the test. It is accepted that any task requiring rapid processing of information will be correlated to rapid processing in another task (Peter et al., 2019). For the DIFF task, reaction times were best predicted by SWE test that required rapid neural processing and subsequent responses. Thus, the ability of the participants to react to the auditory tone stimulus rapidly, process the information, and lastly, use their stored auditory memory representations to elicit a chosen response, was most impacted by how efficient their neural processing speed is when presented with any rapid stimulus. Thus, reaction times in this instance were increasingly influenced by individual neural processing speeds rather than motor response rates.

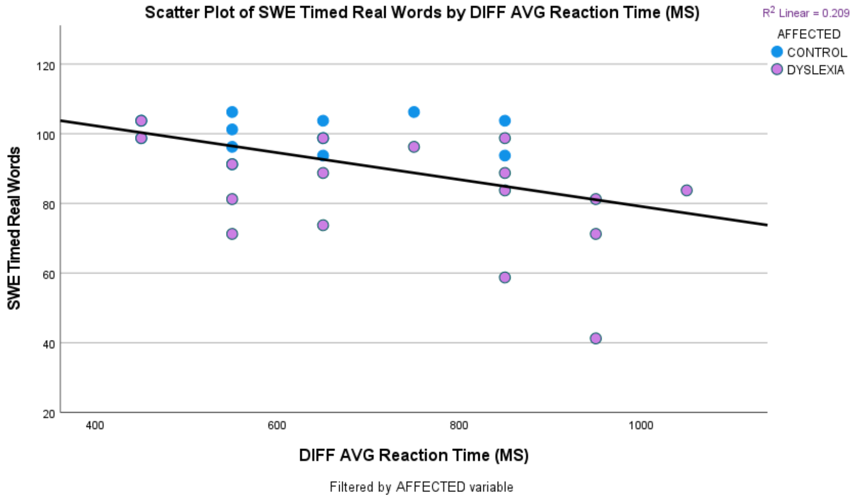

Figure 8 Scatter Plot Displaying Relationship Between DIFF Reaction Time and the SWE Scores Using the Combined Linear Regression Model for Data

Significance

Dyslexia is a multifactorial disorder that manifests in numerous complexities and severities. This study aims to better understand the mechanisms underlying the observed phenotypic dysfunctions and help to illuminate the path to novel methodologies and techniques to alleviate the personal struggles those with dyslexia face. The difficulties that some young children encounter throughout their introductory years of education due to undiagnosed dyslexia, can interrupt their development, educationally, emotionally, and socially. Early diagnosis, and subsequent intervention, can serve to alleviate years of arduous frustration and can prevent these children from falling behind. A better understanding of the mechanisms that drive dyslexia will serve to better diagnose as well as provide insight on strategies to implement earlier to provide dyslexic children the best toolset available in compensating, learning, and thriving.

Limitations

The linear regression models above, showed evidence of correlations between the variables. However, not every participant produced data for each of the variables in question. This limited population size for each of the tasks and measures, limited the scope and significance of the data. A better understanding of each variable's associative neural processing element(s) and how these processes differ with respect to dyslexia and neurotypicals would serve valuable by expanding the experiment and retesting those participants with missing data points. Additionally, the two groups were not entirely matched for age and sex distribution.

Future Research

The regression models provide evidence that other possible prediction interactions could be present among the variables not yet focused on. The inclusion of a new variable depicting musical experience or training would be beneficial to investigate to determine if musical training at an early age could lessen the associated deficits seen with dyslexia. Additionally, the use of fMRI imaging in conjunction with the EEG data would elicit an increased holistic view of the dyslexic brain and increase the magnitude of significance to this study.

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