Dyslexia Beyond the Word: An Ecological Study of Specific Reading Disorder

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Dyslexia Beyond the Word: An Ecological Study of Specific Reading Disorder

Benjamin T. Carter

A dissertation submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

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ABSTRACT

Dyslexia Beyond the Word: An Ecological Study of Specific Reading Disorder

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This dissertation discusses the effects of dyslexia on reading behavior and cognition. It does so by first outlining the overall incidence of dyslexia, providing current definitions, giving a history of scientific inquiry and discussing relevant contemporary research. Thirteen different analyses are then discussed (ten \textit{a priori} and three \textit{post-hoc}). Individuals with dyslexia were found to have increased fixation duration, first run dwell time, total dwell time, and refixation probability. The dyslexia group was also highly sensitive to lexical predictability. Within the reading network, the BOLD response was depressed in dyslexia during reading in the following regions: the left medial and inferior temporal gyrus, the left temporal pole, the right cerebellum, right occipital gyrus and the right parahippocampal gyrus. A second regions of interest analysis in the reading network revealed dyslexia was associated with a depressed BOLD response to lexical predictability in the following regions: left supplementary motor area, posterior middle frontal gyrus, and the left temporal pole. A regions of interest analysis in the oculomotor network revealed a depressed BOLD response in the following regions during reading: the left parietal eye fields and the cerebellum. One oculomotor region had a depressed BOLD response to lexical predictability due to dyslexia: the left frontal eye fields. This sensitivity to lexical predictability and depression in the BOLD response is suggestive of reduced input into higher cortical areas. Future study should be focused on finding the common origin of this bottom-up deficit.

Keywords: dyslexia, reading, predictability, paragraph
# TABLE OF CONTENTS

**ABSTRACT**

Dyslexia Beyond the Word: An Ecological Study of Specific Reading Disorder

- Incidence & Definition ............................................. 1

**Early Theory**

- 1

**Modern Theory**

- The Phonological-Deficit Hypothesis .......................... 4
- The Multifactorial Hypothesis ..................................... 5
- The Neural Noise Hypothesis ....................................... 5

**Documented Deficits**

- Oculomotor Attention Deficits .................................. 7
- Linguistic Deficits .................................................. 9
- Neurological Deficits ............................................... 10

**Proposal**

- Goals .......................................................................... 12
- Hypotheses ............................................................... 12
- Novelty ........................................................................ 14

**Methods**

- Participant Recruitment ........................................... 14
- Measures ...................................................................... 15
- Materials ...................................................................... 15
- Apparatus .................................................................... 15
- Procedure ..................................................................... 16
- Analysis ....................................................................... 17
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Participant demographics</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>Cognitive test results</td>
<td>41</td>
</tr>
<tr>
<td>3</td>
<td>Student’s T-test results</td>
<td>41</td>
</tr>
<tr>
<td>4</td>
<td>Oculomotor profiles</td>
<td>41</td>
</tr>
<tr>
<td>5</td>
<td>Significance of group differences</td>
<td>41</td>
</tr>
<tr>
<td>6</td>
<td>First fixation</td>
<td>41</td>
</tr>
<tr>
<td>7</td>
<td>First run dwell time</td>
<td>43</td>
</tr>
<tr>
<td>8</td>
<td>Total dwell time</td>
<td>43</td>
</tr>
<tr>
<td>9</td>
<td>Intercorrelations of cognitive subtest scores</td>
<td>44</td>
</tr>
<tr>
<td>10</td>
<td>Factor loadings from Principle Components Analysis</td>
<td>45</td>
</tr>
<tr>
<td>11</td>
<td>Changes in group assignment from factor analysis</td>
<td>46</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>Regions of Interest and Gray Matter Mask</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>Distribution of cognitive test scores</td>
<td>42</td>
</tr>
<tr>
<td>3</td>
<td>Whole brain response to paragraphs by group</td>
<td>43</td>
</tr>
<tr>
<td>4</td>
<td>The effect of group and lexical predictability on first fixation duration</td>
<td>44</td>
</tr>
<tr>
<td>5</td>
<td>The effect of group and lexical predictability on first run dwell time</td>
<td>45</td>
</tr>
<tr>
<td>6</td>
<td>The effect of group and lexical predictability on total dwell time</td>
<td>46</td>
</tr>
</tbody>
</table>
Dyslexia Beyond the Word: An Ecological Study of Specific Reading Disorder

Incidence & Definition

Reading is a critical skill necessary for survival in a world dominated by information technology (Snow, Burns, & Griffin, 1998). Without it educational opportunities and income potential are severely limited. Early reading achievement is positively associated with educational status (Lee, Daniels, Puig, Newgent, & Nam, 2008), employment (Caspi, Wright, Moffitt, & Silva, 1998) and wages earned (Arnbak, 2004; McLaughlin, Speirs, & Shenassa, 2014). One obstacle faced by many students learning to read is dyslexia. S. E. Shaywitz, Escobar, Shaywitz, Fletcher, and Makuch (1992) estimated dyslexia’s prevalence to be 9% of boys and 6.0% of girls in the third grade while others estimate it may have an incidence as high as 10% in the general populace (Siegel, 2006). Discrepancies between estimates are probably heavily influenced by the definition of dyslexia used in each study (Rodgers, 1983; B. A. Shaywitz, Fletcher, Holahan, & Shaywitz, 1992; Siegel, 2006).

The current definition of dyslexia from Lyon, Shaywitz, and Shaywitz (2003) is as follows:

Dyslexia is a specific learning disability that is neurological in origin. It is characterized by difficulties with accurate and/or fluent word recognition and by poor spelling and decoding abilities. These difficulties typically result from a deficit in the phonological component of language that is often unexpected in relation to other cognitive abilities and the provision of effective classroom instruction. Secondary consequences may include problems in reading comprehension and reduced reading experience that can impede the growth of vocabulary and background knowledge.

Early Theory

The definition of dyslexia has evolved over time. Dyslexia’s discovery was concurrent with a rise in general literacy during the end of the 19th century. The German
ophthalmologist, Dr. Rudolf Berlin, first coined the term dyslexia in his book *Eine besondere art der wortblindheit (dyslexie)*, published in 1887. In it he described six peculiar cases in which individuals struggled to read yet were of normal intelligence and without ocular abnormalities. Berlin believed this condition was neurological in origin, hypothesizing it was due to a depletion in the conductivity of the connecting fibers of the lower parietal lobe. In support of his hypothesis Berlin reported lesions of the supramarginal and angular gyri were discovered during postmortem examinations of similarly afflicted individuals (Berlin, 1887). Shortly thereafter cases of dyslexia began to appear in the medical literature. Multiple etiologies were proposed. For example, Hinshelwood (1896) reported a case in *The Lancet* in which an alcoholic was cured of toxic dyslexia after abstaining for a period of seven weeks and remained cured for the rest of his abstinent life. Cases of congenital 'word blindness' also began to appear. Morgan (1896) observed a 14 year old boy who struggled to read and spell despite normal intelligence. Other cases were recognized and it became apparent that dyslexia was more complicated than previously thought.

Eventually acquired dyslexia (alexia) and developmental dyslexia diverged as two separate phenomena, the former being the result of pathology and the latter being present from a young age and without a medical explanation. Samuel T. Orton (1925) first made this distinction after meeting a young girl who could not read and had symptoms similar to stroke victims without a prior medical history of neurological pathology. He later developed a theory of 'strephosymbolia' (twisted symbols) describing individuals who struggled to associate word phonology (sound) with orthography (symbology). Once this distinction was made, researchers began to propose physiological causes. Orton proposed dyslexia was a result of incomplete hemispheric dominance (1928). Other theories included delayed myelination of the cerebral cortex (Sinclair, 1948) and differences in the oculomotor centers (Jossmann, 1948).
Modern Theory

Clinically, dyslexia has been redefined as a specific learning disorder with a basis in genetic, epigenetic and environmental factors and is characterized at the cognitive level by difficulty with accurate or fluent word recognition, decoding, and poor spelling abilities. The impairment must be present for at least 6 months, with academic performance significantly below what would be expected according to intelligence and chronological age and cannot be better accounted for by sensory deficit, disability or other disorder. Onset typically occurs during formal schooling but may not be fully manifest until demands exceed capacity (American Psychiatric Association, 2013). The ICD-10 refers to dyslexia as specific reading disorder and gives it essentially the same definition as the DSM-V (World Health Organization, 1992).

Some quantitative guidelines have been suggested. The ICD-10 recommends that reading accuracy and/or comprehension must be at least 2 standard errors below what would be expected based on age and intelligence or a history of reading difficulties with a spelling test at least 2 standard errors below what would be expected. A minimum IQ of 70 on a standardized test is also recommended (see World Health Organization, 1993, pp. 144-145). The DSM-V gives similar recommendations (a minimum IQ of 70 and a score on a standardized reading assessment that is 1.5 standard deviations below the population mean for age). It also recommends that "[o]n the basis of clinical judgment, a more lenient threshold may be used... when learning difficulties are supported by converging evidence from clinical assessment, academic history, school reports, or test scores" (American Psychiatric Association, 2013). Practically speaking, developmental dyslexia is diagnosed by this standard in order to capture individuals with less severe degrees of reading disability but who might otherwise go unnoticed. This enables clinicians to diagnose more subtle cases of dyslexia that would only become apparent when the demands of the reading task exceed capacity.

Research has primarily focused on psychological theories of reading to discern
possible mechanisms of dyslexia. Reading is thought to rely on two methods for word identification and lexical access: direct access and phonologically mediated access. Direct access occurs when a word is visually identified via the printed form without having to convert the word into a phonological code to access meaning. Phonologically mediated access occurs when a word is seen and meaning is accessed first by decoding the sound of the word and then using this phonological recreation to access word meaning. Theoretically, sensory or processing deficits impacting either method could result in reading impairment. Both have been considered as causal candidates for dyslexia.

The Phonological-Deficit Hypothesis

Reading acquisition is highly reliant on phonological or phonemic awareness. Phonological awareness can be described as an individual’s "knowledge of the internal sound structure of spoken words" (Rayner, Foorman, & Perfetti, 2001, p. 37). Reading also relies on other abilities including the ability to see and visually distinguish between orthographic representations and overall intelligence.

Dyslexia is prominently thought to be based in a deficit in phonological processing, termed the Phonological-Deficit Hypothesis (Castles & Friedmann, 2014). Dyslexic children have been shown to have deficits in phoneme based tasks (Harm & Seidenberg, 1999; Rayner et al., 2001). Phonemes are the simplest units making up words within a language. Phoneme processing deficits impair the mapping of speech sounds to semantic meaning. Impaired semantic representations then affect orthographic mapping, which results in reading difficulty. This theory is not without its flaws. The base assumptions of the hypothesis are that phonological deficits are the sole cause of dyslexia and therefore all dyslexic children have a phonological deficit (Castles & Friedmann, 2014). This is not the case. Not all children with dyslexia have been found to have a phonological deficit (White et al., 2006). A number of different types of dyslexia have been suggested (Castles & Friedmann, 2014).
The Multifactorial Hypothesis

Reading is a highly complex behavior, relying on the cooperation of multiple systems within the brain for healthy function. There may be multiple points of failure which could result in reading difficulty (Castles & Friedmann, 2014; Rayner et al., 2001). This has resulted in a multifaceted approach in which phonological deficits are not viewed as the sole cause of dyslexia, with some cases resulting from a failure of sensory integration. For example, direct access is also impaired in some cases, as manifested by deficits in rapid automatized naming (RAN) tasks. RAN tasks assess the ability to quickly name aloud familiar visual stimuli such as shapes or single letters and is believed to be testing the integrity of visual-verbal associations (Norton, Beach, & Gabrieli, 2015). RAN deficits were initially proposed as both a core cause and an augmenting factor as part of the double deficit hypothesis proposed by Wolf and Bowers (1999). Recent investigations have shown deficits in RAN to more likely be moderating rather than causal factors. Catts, McIlraith, Bridges, and Nielsen (2016) has proposed that there is no singular deficit that will yield a dyslexic phenotype, but rather a combination of deficits (many of which are discussed later).

Many subtypes of dyslexia have been proposed including surface dyslexia, letter-position dyslexia, and attentional dyslexia (Castles & Friedmann, 2014). There is debate as to whether these subtypes represent distinct forms of dyslexia or whether they are simply the result of interacting risk factors with phonological deficits as the primary cause of impairment (Castles & Friedmann, 2014; Catts et al., 2016). Testing for these proposed subtypes has not been standardized and they are not utilized in clinical practice.

The Neural Noise Hypothesis

A third potential cause of dyslexia lies with changes in cortical circuitry and neuronal migration. Gross neural activity is not an all or nothing response but is actually quite chaotic and 'noisy.' It is a conglomerate of the activity of many neurons. Much of
this activity is random, secondary to aberrant neurotransmitter release, reduced neurotransmitter clearance, and random fluctuations of ion concentrations across neuron membranes. As a result any signal of significance must be both 'loud' enough to be detected and short enough to reduce its potential contribution to overall noise within the system. This is accomplished via local excitation-inhibition circuits in which significant signals are amplified and then cut off through a feedback-inhibition loop. Errors in signaling can be a result of dysfunctional excitation-inhibition. Slowed inhibitory signals result in increased signal duration and increased noise within a system. Early inhibition results in reduced signal strength. This results in faulty signal transmission and computation.

Errors in the timing of the excitation-inhibition feedback loop could explain some of the features of dyslexia (Hancock, Pugh, & Hoeft, 2017). Deletions of the Dcde2 gene were found in 19% of individuals with developmental dyslexia in a study by Wilcke et al. (2009). Dcde2 deletions in the rodent model have been shown to have increased glutamatergic signaling and expression of the NMDA receptor, NMDA excitability, increased spontaneous activity and spike timing variability (Che, Girgenti, & LoTurco, 2014; Che, Truong, Fitch, & LoTurco, 2016). These models have also demonstrated impaired rapid auditory processing and memory (Centanni et al., 2016; Truong et al., 2014). These increases in glutamatergic activity would result in increased baseline neural activity, resulting in impairment in auditory processing. Magnetic resonance spectroscopy has likewise substantiated this possibility. Increased concentrations of glutamate have been observed in dyslexics in the occipital visual areas and are predictive of reading skill (Pugh et al., 2014). Left lateralized gene expression for glutamatergic signaling in the superior temporal gyrus and auditory cortex have also been observed (Karlebach & Francks, 2015). Therefore excess glutamate activity may be a potential explanation.

Errors of neuronal migration can also give rise to increased neural noise via altered circuit structure and atypical synaptic development. Both Dcde2 and Kiaa0319 deletions
ECOLOGICAL DYSLEXIA

have been shown to alter the neural migration process in the animal model. *Dcdc2* has been linked to reduced dendrite growth and abnormal migration (Meng et al., 2005). *Kiaa0319*, also linked to dyslexia (Paracchini D Phil et al., 2008), is associated with GABAergic interneuron and pyramidal neuron migration (Szalkowski et al., 2013). Normal cortical circuitry is unlikely in the face of these mutations in humans and would result in changes in the timing of the excitation-inhibition cycle, resulting in neural noise that could interfere with normal processing.

**Documented Deficits**

**Oculomotor Attention Deficits**

Eye movements during reading are a series of "stop and go" movements (Erdmann & Dodge, 1898). Eye movements fall into two different categories – saccades and fixations. Saccades are the ballistic movement of the eye from one visual target to the next. Fixations are periods when the eye is not moving and is training the fovea on a visual target. Visual information is gathered and processing is initiated during a fixation. The next saccade is also planned. The temporal duration of a fixation is directly related to the cognitive effort and attention required to process the target. Eye movements during reading are composed of a series of fixations and saccades as the eye is directed from one word to the next. Words such as "the" or "a" are often skipped. Words that are longer, unfamiliar, or linguistically unpredictable receive longer fixations.

Eye movements were among the early features studied in dyslexia (Jossmann, 1948). Eye tracking studies have been used to make inferences concerning cognitive and linguistic processes in healthy individuals and have thus been applied to dyslexia. Early studies demonstrated saccadic irregularity and frequent reversal errors compared to healthy readers (Jossmann, 1948). More recent studies have confirmed and extended these findings. Individuals with dyslexia skip fewer words, make multiple fixations on more words, regress more frequently and fixate longer (Biscaldi, Gezeck, & Stuhr, 1998; Hawelka, Gagl, &
Wimmer, Hutzler & Wimmer, McConkie et al. There is also a marked effect of word length (De Luca, Borrelli, Judica, Spinelli, & Zoccolotti. Hawelka et al., 2010). Visuo-attentional deficits have also been identified in dyslexia and this may be contributing to reading deficits by impairing orthographic and phonological processing (Bellocchi, Muneaux, Bastien-Toniazzo, & Ducrot, 2013, Facoetti, Corradi, Ruffino, Gori, & Zorzi, 2010). Word predictability has also been shown to have a potential effect. Hawelka, Schuster, Gagl, and Hutzler (2015) found individuals with dyslexia had decreased reading speed when word predictability was reduced, indicating impairment of linguistic prediction. While informative, all of these studies utilized stimuli composed of single words or isolated sentences to study eye movements and therefore have reduced ecological validity. None have observed how an individual with dyslexia reads a paragraph of text – the most common reading environment. More work must be done to define how these behaviors extend to reading a page of text and the effects of text characteristics on reading behavior and comprehension in dyslexia. Such information would allow for the creation of guidelines to facilitate the creation of an orthographic environment to accommodate individuals with dyslexia. It is also debatable as to whether dyslexia is purely a linguistic deficit (De Luca, Di Pace, Judica, Spinelli, & Zoccolotti, Lukasova, Silva, & Macedo, 2016). Individuals with dyslexia appear to have impaired oculomotor performance even in non-reading tasks. Lukasova et al. (2016) demonstrated increased latency in a saccadic prediction task, which is not a language based task. Prediction deficits therefore may not be isolated to language alone and have a basis within the executive control of oculomotor centers. This may negatively impact learning to read and reading fluency.

The effect of an ecological reading environment on oculomotor attention and behavior in dyslexia is not well studied. While earlier studies such as Jossmann did utilize page-based reading measures, few since have utilized this method. Using the Web of Science Core Collection (Reuters, 2012) and the terms "dyslexia" and "eye tracking" only returns 56 studies (as of March 5, 2018). Refining these results with the terms "page,"
'paragraph,' "connected text," or "continuous text' reveals zero, three, zero and one result, only one of which directly addresses dyslexia in a paragraph based reading environment (Rello & Baeza-Yates, 2017). This particular study focuses exclusively on the effect of orthographic and format-related features of text on comprehension in dyslexia rather than linguistic factors.

Linguistic Deficits

A hallmark of dyslexia is difficulty learning new words and grammar rules (Lyon et al., 2003). Language learning heavily relies on statistical and procedural learning skill (Christiansen & Chater, 2016; Dell & Chang, 2014; Krishnan, Watkins, & Bishop, 2016) so procedural learning has been studied to determine its role in dyslexia. Ullman and Pierpont (2005) first proposed the involvement of the procedural learning system as a potential explanation for language learning deficits. Serial reaction time (SRT) protocols have been used to test procedural learning abilities in children with dyslexia in a number of studies. A recent meta-analysis of these studies by Lum, Ullman, and Conti-Ramsden (2013) found dyslexia had a significant effect ($p < 0.001$) on task performance, demonstrating that individuals with dyslexia were noticeably impaired in the SRT paradigm, and thus had impaired procedural learning. Statistical and grammar learning are also impaired. Pavlidou, Kelly, and Williams (2010) found that children with dyslexia performed similarly to age-matched controls in a memorization task, but struggled in an implicit artificial grammar learning task, which indicates impaired rule abstraction. Gabay, Thiessen, and Holt (2015) found that adults with dyslexia were impaired in a statistical learning task in which they were asked to differentiate between two strings of syllables and determine which string best matched a preceding third string. Performance was found to correlate with reading ability. The impairment persisted even when non-linguistic stimuli were used, demonstrating that it was not limited to language learning. Gabay has also demonstrated that individuals with dyslexia are impaired in other probabilistic learning tasks such as
weather prediction (Gabay, Vakil, Schiff, & Holt, 2015) and auditory category learning (Gabay & Holt, 2015). Sigurdardottir et al. (2017) likewise demonstrated statistical learning impairment via the use of a shape memorization and recognition task. Impairments of statistical and grammatical learning would all impact the ability to predict features of upcoming text. Impaired statistical learning would result in difficulty making inferences based on previous experience (i.e. what had been previously read). Impaired grammatical learning would cause difficulty in predicting sentence structure, word order and composition. This could result in an overall inability to predict linguistic features of text and difficulty achieving normal reading fluency and comprehension. Changes in text predictability would then serve to either facilitate or confound reading and be linked with cognitive and attentional responses.

**Neurological Deficits**

No studies have been conducted to date examining the hemodynamic responses in individuals with dyslexia using a paragraph–based reading environment. To confirm this the terms 'dyslexia', 'fMRI', and 'paragraph' or 'continuous text' or 'connected text' were used to search the Web of Science Core Collection (Reuters, 2012) for relevant studies. None were found using these terms—which was surprising. Paragraphs are highly common and are regularly encountered in books, magazines, web pages, computer and mobile applications. This makes paragraphs a natural choice as stimuli. Studying reading deficits in this environment would give a holistic picture of the condition and as well as control for any changes in cognition resulting from simplifying stimuli. This study aims to fill this gap in the literature.

Studies of dyslexia have utilized single sentences as stimuli. Christodoulou et al. (2014) studied reading fluency in developmental dyslexia by presenting sentences in a single word format (i.e. each word was individually displayed in a serial manner). As presentation rate increased, normal readers had significantly higher activations in the left prefrontal
cortex and left superior temporal cortex than dyslexic readers. While not a natural reading environment this study does demonstrate reduced activation in the dyslexic model in regions associated with the phonological component of language processing and represents a step in the right direction. Sentences, even in a serial presentation paradigm, are more ecologically relevant than a single word presented in isolation from linguistic context.

Other methodologies have previously been applied to isolate regions of interest. Phonologically based tasks have successfully observed changes in the insular cortex (Steinbrink, Groth, Lachmann, & Riecker, 2012), medial geniculate body (Diaz, Hintz, Kiebel, & von Kriegstein, 2012), left inferior frontal gyrus (Dufor, Serniclaes, Sprenger-Charolles, & Demonet, 2009, Karni et al., 2005, MacSweeney, Brammer, Waters, & Goswami, 2009, Peyrin et al., 2012), left middle frontal gyrus, left precuneus, left inferior parietal lobule, superior temporal gyrus (Pecini et al., 2011), and left occipitotemporal areas (Conway et al., 2008, Karni et al., 2005, McCrory, Mechelli, Frith, & Price, 2005). Procedural-based learning tasks have also identified regions of interest including the corticostriatal circuits and the hippocampus (Krishnan et al., 2016). These regions may be relevant to dyslexia. Procedural learning is central to learning phonology, grammar and orthography (Christiansen & Chater, 2016, Dell & Chang, 2014). Deficits in these abilities could contribute to impaired literacy by interfering with language acquisition. However, their contribution to the dyslexia phenotype has not been fully elucidated and requires additional study.

Unfortunately, serial presentation methods, single word presentation, phonological tasks and procedural-based tasks fall short of ecologically valid stimuli. This creates a deficit in validity and these findings may not be preserved in the face of a more natural reading environment. Additional study is necessary to determine if and to what extent these functional differences are preserved when engaged in normal reading.
Proposal

Goals

The goals of the study were as follows: (1) confirm whether previous findings of hemodynamic function using single words or serial presentation paradigms are replicable using paragraphs, and (2) characterize differences in attention and cognition in dyslexia when reading and responding to text predictability. The following hypotheses and experiments are proposed in support of these aims.

Hypotheses

_Hypothesis 1: Can previous findings be duplicated using paragraph based stimuli?_

If dyslexia is neurological in origin then there should be a common behavioral and physiological phenotype. Past use of simplified stimuli has revealed some differences. If past findings are relevant to dyslexia then they will be present when using paragraph based stimuli. These hypotheses will be tested using the following experiments.

_Supporting Experiments._

1. Compare the oculomotor behavioral profile of a individuals with dyslexia with a healthy control group while reading paragraphs, measuring: first fixation time, total fixation time, regression probability, and refixation probability (see Hypothesis 1, Analysis 1).

2. Compare the hemodynamic response of a dyslexic test group with a healthy control group while reading paragraphs using whole brain analysis (see Hypothesis 1, Analysis 2).

3. Test for differences in the BOLD response to paragraphs between groups in the reading network (see Hypothesis 1, Analysis 3).
4. Test for differences in the BOLD response to paragraphs between groups in the eye fields (see Hypothesis 1, Analysis 4).

5. Test for differences in the BOLD response to paragraphs between groups in the striatum (see Hypothesis 1, Analysis 5).

**Hypothesis 2: Can dyslexic and healthy cognition be characterized using linguistic predictability?**

If dyslexia impairs probabilistic learning then this impairment should generalize to difficulty predicting and responding to linguistic features of text. Attention and cognition supporting prediction will be measurably different from otherwise healthy cognition and be directly associated with the linguistic features of text, i.e. lexical predictability.

**Supporting Experiments.**

1. Compare the oculomotor behavioral profile of a dyslexic group with a healthy control group while reading paragraphs, measuring the influence of lexical predictability of the currently fixated word on reading times (see Hypothesis 2, Analysis 1).

2. Test for differences in the BOLD response to linguistic predictability using whole brain analysis (see Hypothesis 2, Analysis 2).

3. Test for differences in the BOLD response to lexical predictability in the reading network (see Hypothesis 2, Analysis 3).

4. Test for differences in the BOLD response to lexical predictability in the eye fields (see Hypothesis 2, Analysis 4).

5. Test for differences in the BOLD response to lexical predictability within the striatum (see Hypothesis 2, Analysis 5).
Novelty

Functional studies of dyslexia have previously used limited stimuli including single word or sentence reading via serial presentation paradigm. This is unfortunate as the most pronounced effects of dyslexia become apparent in a normal reading environment which is paragraph–based. This lack of data in the field of dyslexia makes this study a valuable addition to current literature by determining if previous findings extend into ecological reading environments and allows us to search for changes in oculomotor and hemodynamic function specific to this environment. This study will also utilize some of the recommendations put forth by Ramus, Altarelli, Jednorog, Zhao, and Scotto di Covella (2017), including increased statistical power and the use of predefined regions of interest in the functional and structural analysis.

Methods

Participant Recruitment

All participants were recruited from Brigham Young University, Utah Valley University and the surrounding community. Inclusion criteria for the control group were as follows: a minimum IQ score of 70>5 (American Psychiatric Association, 2013), right handed, literate native English speakers, normal vision and no history of neurological disorder, psychiatric disorder, reading disability, and 18-35 years of age. Participants could not have any contraindications to an MRI study including pregnancy, metallic or unidentified foreign objects within their body, non-MRI compatible prosthetic devices, stents, shrapnel, metal fragments, or claustrophobia.

Participants in the dyslexic group met the same inclusion criteria as the control group with the addition of a diagnosis of dyslexia or specific reading disorder. Diagnosis was confirmed using the Gray Oral Reading Test V, Comprehensive Test of Phonological Processing 2, and Weschler Adult Intelligence Scale 2. For the purposes of this study and as suggested in the DSM-5, clinical judgement took precedence over the results of any single
test, thus allowing for the inclusion of participants with subtle impairment. Individuals with dyslexia were compensated $100 for participation, and $50 for the control group.

Measures

All participants were tested using the Gray Oral Reading Test (GORT-5) (Hall & Tannebaum, 2013). Participant intelligence was assessed via the Wechsler Abbreviated Scale of Intelligence (WASI-II) (McCrimmon & Smith, 2013). Phonological ability was assessed via the Comprehensive Test of Phonological Processing (Wagner et al., 1999). All tests were administered by a trained research assistant and scored by a trained graduate student.

Materials

Participants were presented with 54 paragraphs of text that are a subset of Luke and Christianson (2016). These passages were drawn from a myriad of sources that include news articles and works of literature in the public domain. These passages were approximately 50 words in length and averaged 2.5 sentences per paragraph. Each word received a predictability rating via a cloze procedure as outlined in Luke and Christianson (2016) for lexical, syntactic and semantic predictability.

Apparatus

Stimuli were presented using a 24-inch BOLDScreen from Cambridge Research Systems, an MRI-safe LCD monitor at a resolution of 1600×1200 pixels. Text were displayed in Courier New font 35 pt, so that approximately 3.5 letters subtend to 1 degree of visual angle. Eye-movements were recorded via a monocular SR Research Eyelink 1000 plus long-range MRI eye-tracker sampling at 1000Hz.
**Procedure**

Eye-tracking and fMRI data were obtained first in six 5.4 minute runs. Each functional run included nine paragraphs and nine images. Participants were instructed to read the paragraphs silently and to not make use of their mouths while reading to minimize movement in the scanner. They were also told to read at a normal pace and that they are not required to finish the paragraph within the allotted time and that it was expected they may not finish it. They were instructed to look at an X in the bottom right-hand corner of the screen should they finish the paragraph before time expires. Finally, participants were instructed to read the paragraphs so they could recall them for later questioning. Within each run, the order of paragraph presentation was randomized for each participant. Prior to each paragraph a fixation cross was presented at the location of the first word of the subsequent paragraph. Paragraphs were presented for 12 seconds, with a 6 second inter-trial interval in which the participant was presented with another fixation cross.

**Eye-movement Data Acquisition**

Each functional run was preceded by a nine-point calibration to ensure accurate measurement. Error during calibration was limited to an average of less than 0.49 visual degrees of angle and a maximum error of 0.99 degrees of visual angle. Prior to each trial and during the inter-trial interval a fixation cross was presented at the location of the first word in the paragraph. Stimulus presentation and eye position recording were controlled by software from SR Research.

**fMRI Data Acquisition**

A Siemens 3T Tim Trio was be used for this study with a 12-channel receive-only head coil. Software version was Syngo MR B17 DHHS. Three consecutive blocks of functional scans were performed using an interleaved T2* weighted echo-planar imaging; slice number 43, orientation was transverse, phase encoding direction was anterior to
posterior, rotation was 0, FOV= 224x224, matrix 64x64, slice thickness 3.0 mm, TR 2500 ms, TE 28 ms, 134 repetitions, and a flip angle of 90°.

**Structural Data Acquisition**

A structural scan was performed using T1-weighted imaging; orientation was sagittal, anterior to posterior phase encoding, FOV=218x250, matrix 256x256, slice thickness 1.00 mm, TR 1900 ms, TE 2.26 ms, flip angle was 9°. Conventionally, structural scans are performed prior to any functional scans. Functional scans were performed prior to the structural scans in this study in order to compensate for the effects of participant fatigue and somnolence.

**Coregistration of Eye-movement and fMRI Data**

The experiment was programmed so that the stimulus presentation did not begin until the functional scan had begun. A timestamp for scan onset was received by Experiment Builder software and stored in the data and used to compute trial and word fixation onset times.

**Analysis**

**Eye Tracking Analysis**

DataViewer (SR Research Ltd, version 1.11.1) was used to view the eye tracking data. Saccades were defined as eye movements as the eye traveled from one target to another. Fixations were defined as occurring between saccades and without an intervening blink. Fixations with a duration less than 50 ms and greater than 1500 ms were excluded. Fixations were excluded from the study if they did not fall on a word. Saccades were considered a regression if they end on a previously fixated word. Data was then exported in a tab-delimited format and analyzed using R (R Core Team, 2016).
**Group Structural Model Creation**

Structural T1-weighted images were preprocessed with **dcm2niix** (Li, Morgan, Ashburner, Smith, & Rorden, 2016) and aligned via the anterior and posterior commissures by **ACPCdetect** (Ardekani & Bachman, 2009). Participant scans underwent bias field corrections using **N4BiasCorrection** (Tustison et al., 2010) and normalized to MNI space via the ICBM 152 template (Collins, Zijdenbos, Baaré, & Evans, 1999; V. S. Fonov, Evans, McKinstry, Almli, & Collins, 2009; V. Fonov et al., 2011) via ANTs. Participant scans were then used to construct a study specific template via **buildtemplateparallel.sh** (Avants et al., 2011; Klein & Tourville, 2012). This was then segmented using the Desikan-Killiany-Tourville protocol via **antsJointLabelFusion.sh** using the OASIS-TRT-20 database of atlases (Klein et al., 2017; Klein & Tourville, 2012; Tustison et al., 2014; Wang et al., 2013). A binary gray matter mask was then created by joining labels via Convert3D (Yushkevich et al., 2006).

**fMRI Analysis**

Data were analyzed using the Analysis of Functional NeuroImages (AFNI) software program (Cox, 1996) and Advanced Normalization Tools (Avants et al., 2011). Functional imaging were converted from DICOM imaging format to native BRIK and HEADER formats via **to3d** for analysis in AFNI. T1-weighted images were co-registered to the third functional scan imaging using **3dWarp**. Functional scans were then corrected for motion and slice time corrections were applied using the 69th TR as a reference via **3dvolreg**. The first and second blocks were then corrected for motion relative to the third block, also via **3dvolreg**. A mask was then created for each subject via **3dSkullStrip** and used to restrict the analysis to only brain matter. Individual input matrices were constructed and deconvolution performed via **3dDeconvolve**, with 6 regressors coding for motion (pitch, roll, yaw, superior-inferior translation, left-right translation and anterior-posterior translation). Regressors of interest were coded according to the hypothesis tested and the reader is
referred each experiment for greater detail. Deconvolution of the BOLD response was then performed via 3dDeconvolve. A 5mm blur was applied via 3dmerge and individual anatomical and statistical maps were projected using a study specific template aligned to standard MNI_152 space (Collins et al., 1999; V. S. Fonov et al., 2009; V. Fonov et al., 2011) via ants.sh (Avants et al., 2011). A random effects analysis comparing the healthy and dyslexia groups was then performed via 3dttest++, and an anatomical mask was used to restrict the analysis to gray matter. A voxel-wise threshold of \( p < 0.001 \), cluster-size threshold > 39, were then applied for an \( \alpha < 0.05 \) as determined via the -Clustsim option.

**Regions of Interest Selection**

Regions of interest included the oculomotor network, reading network, and prediction were identified using a large-scale automated meta-analysis of current fMRI literature via Neurosynth (Yarkoni, Poldrack, Nichols, Van Essen, & Wager, 2011). The eye field regions of interest were created using an automated meta-analysis using the term "eye movement." The reading network regions of interest were created using the term "reading." The prediction regions of interest were created using the term "prediction." Association maps were created with a FDR of 0.01. These were then converted to labeled areas of interest via 3dClusterize. Voxels were assigned to a cluster if they had a z-score > 0.01, shared a face with a neighboring voxel (nearest neighbors = 1) with a minimum cluster size of 40 voxels. Participant maximum activation for each \( a \ priori \) region was calculated and extracted via 3dROIstats for both the reading and lexical predictability conditions. This was then entered into a linear model with participant group as the explanatory variable and maximum activation as the response variable.

**Participant Characteristics**

A total of 45 participants were recruited for this study. All were either current students or former students of Brigham Young University or Utah Valley University. Both groups were similar in terms of age, gender distribution, ethnicity and race (see Table 1).
Differences were present between groups when examining both gross intelligence (assessed via the WASI-II), reading ability (assessed via the GORT-5) and phonological ability (assessed via the CTOPP-2), see Table 2. For intercorrelations between the scores see Table 9.

Table 1

<table>
<thead>
<tr>
<th></th>
<th>level</th>
<th>Control</th>
<th>Dyslexia</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td></td>
<td>21</td>
<td>24</td>
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<tr>
<td>Gender (%)</td>
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<td></td>
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<td>14 (66.7)</td>
<td>14 (58.3)</td>
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<tr>
<td>Male</td>
<td></td>
<td>7 (33.3)</td>
<td>10 (41.7)</td>
</tr>
<tr>
<td>Age (mean (SD))</td>
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<tr>
<td>Ethnicity (%)</td>
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<tr>
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<td>3 (12.5)</td>
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<tr>
<td>Not Hispanic or Latino</td>
<td></td>
<td>20 (95.2)</td>
<td>21 (87.5)</td>
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<td>Race (%)</td>
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<td>0 (0.0)</td>
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<td>3 (12.5)</td>
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<td>20 (95.2)</td>
<td>21 (87.5)</td>
</tr>
<tr>
<td>Documentation (%)</td>
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<td>5 (20.8)</td>
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<tr>
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<td>19 (79.2)</td>
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<tr>
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<td></td>
<td>16 (76.2)</td>
<td>10 (41.7)</td>
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<tr>
<td>Other psychiatric disorders (%)</td>
<td></td>
<td>Yes, one or more of the above.</td>
<td>5 (23.8)</td>
</tr>
</tbody>
</table>

Note: Of the participants who were not currently attending a university, all had attended a university in the past.

Hypothesis 1 - Confirming Previous Findings

Analysis 1 - Oculomotor Differences

The purpose of this analysis was to examine the oculomotor profiles of each group and determine whether group differences were present, even after controlling for the characteristics of the text. If the findings of previous studies using simplified text are valid, then they should extend to more ecologically valid and complex reading environments.
Analysis

Oculomotor data were analyzed in R (R Core Team, 2016). Summary statistics were then computed for each participant and then compared between groups via Student’s T-test.

Results

The dyslexia group displayed increased mean first fixation duration, first run dwell time, total dwell time (total time viewing a word during a trial), as well as higher refixation probability (see Tables 4 and 5).

Analysis 2 - Hemodynamic Differences

Analysis

This analysis searched for group differences in the BOLD response to paragraphs of text. The purpose of this analysis was to determine whether previous findings of the dyslexic response to text were replicable using paragraphs rather than simplified stimuli. Ideal hemodynamic response functions were created using the appearance of a paragraph on-screen as the onset of an interest period. Each interest period had a duration of 12 seconds to create a boxcar design. This was contrasted against periods when a fixation cross was displayed. This allowed for the examination of the BOLD response to paragraphs of text for each individual. Group maps were then constructed and compared via 3dttest++ to search for whole brain group differences. See the section on MRI Analysis for more information on preprocessing.

Results

No significant differences emerged between groups.
Analysis 3 - ROI Analysis of the Reading Network

The purpose of this test was to determine whether the magnitude of the BOLD response within reading network regions was associated dyslexia. After deconvolution (see the previous section), individual participant activations within each region of the reading network were extracted from the participant’s template aligned statistical map of their response to reading via 3dROIstats. These were then entered into a linear model with participant diagnosis as the explanatory variable and activation within the eye field as the response variable.

Results

Dyslexia was found to be associated with reduced activation in five regions: the left middle and inferior temporal gyrus, $F(1,43) = 4.14, p = 0.0482, \beta = -0.656, R^2 = 0.08776$, the right cerebellum, $F(1,43) = 14.3, p = 0.000475, \beta = -0.4603, R^2 = 0.2496$, the right occipital gyrus, $F(1,43) = 6.14, p = -0.659, R^2 = 0.1249$, the left temporal pole, $F(1,43) = 9, p = 0.00448, \beta = -0.572, R^2 = 0.1731$, and the right parahippocampal gyrus, $F(1,43) = 4.85, p = 0.0331, \beta = -0.1602, R^2 = 0.1013$.

Analysis 4 - ROI Analysis of the Eye Fields

The purpose of this test was to determine whether the magnitude of the BOLD response within each of the eye fields was associated with reported diagnosis. To do this, individual participant activations within each of the eye fields were extracted from the participant’s template aligned statistical map of their response to reading via 3dROIstats. These were then entered into a linear model with participant diagnosis as the explanatory variable and activation within the eye field as the response variable.

Results

Two regions had decreased activation in association with dyslexia: the left parietal eye fields, $F(1,43) = 6.58, p = 0.0139, \beta = -0.607$, and the cerebellum, $F(1,43) = 12, p =
0.00124, $\beta = -0.749$.

**Analysis 5 - ROI Analysis of the Caudate and Putamen**

The purpose of this test was to determine whether the magnitude of the BOLD response within right and left caudate and putamen were associated with reported diagnosis. To do this, individual participant activations within each of the eye fields were extracted from the participant’s template aligned statistical map of their response to reading via 3dROIstats. These were then entered into a linear model with participant diagnosis as the explanatory variable and activation within the eye field as the response variable.

**Results**

Activation during reading within the right and left caudate and putamen was not found to be associated with dyslexia when reading.

**Hypothesis 2 - Exploring Linguistic Predictability**

**Analysis 1: Predictability Effects on Oculomotor Behavior**

The purpose of this analysis was to determine whether sensitivity to linguistic predictability differed between groups. To do so, oculomotor data were exported via DataViewer and analyzed in R (R Core Team, 2016), these were then combined with lexical predictability data from Luke and Christianson (2016). Eye movements were then entered into a linear mixed-effects model via lmer, with an oculomotor response variable (e.g. first fixation duration, total dwell time). Explanatory variables included reported diagnosis and the lexical predictability of the fixated word. Random effects were entered for each participant. Statistical significance was then evaluated via lmerTest (Bates, Mächler, Bolker, & Walker, 2015; Kuznetsova, Brockhoff, & Christensen, 2017).
**Results**

Lexical predictability had little effect on the duration of the first fixation. It did however increase the duration of first run dwell time indicating it had a facilitating effect on reading behavior for both groups. It also positively associated with increased total dwell time \((p < 0.001)\) and interacted with group (see Tables 6, 7 and 8), demonstrating an increased influence in dyslexia relative to controls.

**Analysis 2 - Group Differences in BOLD Response to Predictability**

**Analysis**

The purpose of this analysis was to determine if any group differences existed in the hemodynamic response to linguistic predictability. Participants were assigned to groups based on reported diagnosis. Individual hemodynamic response functions were then created using a parametric regressor coding for lexical predictability. A second parametric regressor was then added encoding fixation duration. This resulted in an amplitude and wavelength modulated hemodynamic response function. Group statistical maps were then constructed and compared via 3dttest++.

**Results**

No significant differences were discovered between groups across any of the regressors of interest.

**Analysis 3 - ROI Analysis of the Reading Network**

The purpose of this test was to determine whether the magnitude of BOLD response to lexical predictability in each part of the reading network was associated with diagnosis. After deconvolution, individual participant activations within each region of the reading network were extracted from the participant’s template aligned statistical map of their response to lexical predictability via 3dROIstats. These were then entered into a
linear model with participant diagnosis as the explanatory variable and activation within each region as the response variable.

**Results**

Dyslexia was found to be associated with reduced activation in two regions: one centered on the left supplementary motor area and posterior middle frontal gyrus, $F(1,43) = 6.101, \ p = 0.0176, \ \beta = -2.6823, \ R^2 = 0.1242$, and the left temporal pole, $F(1,43) = 5.303, \ p = 0.0262, \ \beta = -2.0648, \ R^2 = 0.1098$.

**Analysis 4 - ROI Analysis of the Eye Fields**

The purpose of this test was to determine whether the magnitude of BOLD response to lexical predictability in each of the eye fields was associated with diagnosis. After deconvolution, individual participant activations within each region of the reading network were extracted from the participant’s template aligned statistical map of their response to lexical predictability via 3dROIstats. These were then entered into a linear model with participant diagnosis as the explanatory variable and activation within each region as the response variable.

**Results**

One region of interest had decreased activation in the dyslexia group: the left frontal eye fields, $F(1,43) = 4.846, \ p = 0.0331, \ \beta = -2.4093, \ R^2 = 0.1013$.

**Analysis 5 - ROI Analysis of the Caudate and Putamen**

The purpose of this test was to determine whether the magnitude of BOLD response to lexical predictability in each caudate and putamen was associated with diagnosis. After deconvolution, individual participant activations within each region of the reading network were extracted from the participant’s template aligned statistical map of their response to lexical predictability via 3dROIstats. These were then entered into a
linear model with participant diagnosis as the explanatory variable and activation within each region as the response variable.

**Results**

The BOLD response to lexical predictability within the right and left caudate and putamen was not found to be associated with dyslexia.

**Post-Hoc Analyses**

While *a priori* results were promising, it must be acknowledged that the reliability of participant knowledge concerning a diagnosis of dyslexia was at times doubtful. Therefore, several secondary analyses were undertaken to reexamine the findings of the regions of interest analyses. Rather than sort participants by reported diagnosis, we developed a secondary measure of reading impairment via factor analyses. Participants were then ranked and reassigned to a group based on this measure. This resulted in the reassignment of two control participants to the dyslexia group and four dyslexia participants to the control group. The BOLD response of each participant to paragraphs (and not lexical predictability) were then extracted from the same regions and were entered into a linear model, with the composite score as the explanatory and participant $\beta$ values as the response variable.

**Factor Analysis**

In order to create a latent variable that represented group differences, an exploratory factor analysis was conducted. All participant scores from the following tests were used: reading fluency and comprehension from the GORT-5; phonological ability and rapid symbolic naming from the CTOPP-2. These were entered into a principle components analysis with varimax rotation using `princomp` from R (R Core Team, 2016). The largest factor, with an eigen value of 1.46, explained 53% of the variance.
Intercorrelations between these factors are reported in Table 9 and factor loading scores are found in Table 10. Changes in group assignment can be found in Table 11.

**Analysis 1 - a Second Look at the Reading Network**

Of the 12 regions represented in the mask, four had a significant association with the composite measure: the left inferior and middle temporal gyri \((F(1,43) = 7.775, p<0.00786)\) with an \(R^2\) of 0.1531 and \(\beta=-0.2947\), another comprising the right lobe of the cerebellum \((F(1,43) = 10.02, p<0.00284)\) with an \(R^2\) of 0.4234 and \(\beta=-0.13632\), the left medial temporal pole \((F(1,43)=9.636, p<0.0037)\) with an \(R^2\) of 0.6345 and \(\beta=-0.20030\), and the left inferior temporal gyrus \((F(1,43)=5.007, p<0.0305)\) with an \(R^2\) of 0.1043 and \(\beta=-0.05530\). These findings are similar in terms of the regions associated with dyslexia and the direction of the association to that of the \textit{a priori} analysis. Only the parahippocampal gyrus is absent.

**Analysis 2 - a Second Look at the Eye Fields**

Of the 12 regions tested, two had a significant association with the composite measure: the left parietal eye fields \((F(1,43) = 4.825, p < 0.0335)\) with an \(R^2\) of 0.1009, and the cerebellum \((F(1,43) = 7.272, p < 0.00996)\) with an \(R^2\) of 0.1447. Slow reading was associated with a decrease in activation by -0.18025 in the left parietal eye fields, and a decrease of -0.2079 in the cerebellum. This is also a similar result to the \textit{a priori} analysis as well, in that these same regions were negatively associated with dyslexia.

**Analysis 3 - a Second Look at the Striatum**

Participant activation within the caudate and putamen was not found to be associated with the composite measure, the same as in the \textit{a priori} analysis.
Discussion

This dissertation presents the results of an experiment with ten \textit{a priori} and three \textit{post-hoc} analyses, examining reading behavior and cognition in individuals with dyslexia, or specific reading disorder. Twenty-four participants were recruited for the dyslexia group and twenty-one for the control group. Each underwent both fMRI and eye tracking while reading paragraphs of text, followed by a single structural MRI. These data were then used to compare the groups, searching for differences in both gross differences in oculomotor behavior while reading, sensitivity to linguistic characteristics of text, and hemodynamic fluctuation. In the sections that follow, the oculomotor results will first be considered, followed by a discussion of the whole-brain analysis. This is then followed by a discussion of the findings of the regions of interest analyses, organized according to region rather than analysis. Theoretical implications of these findings are then outlined and future directions of research are proposed.

Oculomotor Behavior in Dyslexia

\textit{Reproducing Previous Findings}

Group oculomotor profiles were as expected. Overall the dyslexia group displayed increased first fixation duration, first run dwell time, and total dwell time. This means they spent more time viewing individual words (and therefore fewer words in a trial period) than the control group. Additionally they were more likely to fixated upon a word multiple times before leaving it as demonstrated by the increased refixation probability. This is a general characteristic of readers who are impaired or unskilled relative to their peers and would be expected in dyslexia.

\textit{Effect of Lexical Predictability}

Lexical predictability is a measure of the likelihood of the occurrence of a word in the context of the surrounding text. For example, how likely is it that the word \textit{car} will
appear as the last word of the sentence 'I want to drive the...' as compared to the word airplane? Words with a higher lexical predictability are generally more expected in the context of their text just as car is more expected than airplane. Words with higher lexical predictability receive shorter and fewer fixations than those with lesser predictability.

In this experiment, participants in both groups were found to be sensitive to lexical predictability. Individuals with dyslexia were found to have increased first fixation duration, first run dwell time, and total dwell time relative to controls. Of these, first run dwell time and total dwell time had a significant relationship with lexical predictability (see Tables 7 and 8; Figures 5 and 6). Both had a negative relationship with lexical predictability, indicating the dyslexia group’s reading times were strongly influenced by lexical predictability. The interaction between predictability and group in the total dwell time analysis indicates that dyslexic participants are even more sensitive to predictability than controls.

This demonstrates that individuals with dyslexia are more dependent on predictions of the text while reading than other readers. Impairment in decoding word meaning, either phonologically or orthographically, results in degraded input to higher cognitive centers and increases their reliance on predictions about the text, resulting in increased time fixating upon old words.

What Happened to Group Differences in the BOLD Response?

The lack of group differences in the BOLD response to paragraphs and linguistic predictability was perplexing but not inexplicable. For example, this may simply be due to inadequate statistical power. Both groups have a small sample size (21 in the control and 24 in the test group). It should be noted that the activation maps for each group are somewhat similar in both activation geography and magnitude (see Figure 3) despite differences in their cognitive test scores (see Table 3). It may be that differences between these groups are subtle, requiring a much larger sample size to be detected as a change in
the BOLD response. The fact that this difference appears in the regions of interest-based analysis supports this explanation.

Recruitment for this group was difficult. During the first year of this study we relied exclusively on recruiting through the University Accessibility Centers of Brigham Young University and Utah Valley University and received only four referrals during that time. In order to increase recruitment, we began to advertise the study in the community via fliers and word of mouth. Recruitment increased substantially, but we became more reliant on participants accurately reporting and understanding their diagnoses, which may have been a source of confounding by including individuals in the study who did not have a true diagnosis, misunderstood their diagnosis or who may not have been truthful.

Despite this, all participants were either current or former university students, which could have also been a source of confounding. Our test group is unique in that they were able to meet the requirements for admission at a University. They had previously displayed adequate scholastic aptitude for enrollment, and may have developed their own cognitive compensations for any impairment prior to admission and diagnosis, resulting in increased similarity with normal readers. It is also possible that their individual compensations introduced additional variability within the test group, weakening any potential differences from the control group BOLD response.

It may also be possible that confounding was introduced by potential subgroups of dyslexia. This study did not separate the test group into subgroups based on the degree or absence of phonological impairment. Current evidence suggests individuals can have homogeneous reading profiles and yet have distinct causes of cognitive impairment (Zoubrinetzky, Bielle, & Valdois, 2014). This may be the case here. Additional study is necessary to examine the test group for the presence of subgroups.

Finally, previous studies have demonstrated differences using simplified stimuli (Christodoulou et al., 2014; B. A. Shaywitz et al., 2002) rather than full paragraphs of text. This is the first study to utilize paragraphs of text as stimuli in a study of dyslexia.
It is possible the paragraphs themselves introduced some confounding in the overall BOLD response of the test group. Paragraphs are semantically rich stimuli. One need not look at or decode every word to understand the meaning of the whole text. In fact, no reader ever directly gazes upon every single word in a body of text (unless they are an unskilled reader). This study demonstrates this; even the control group regularly skipped words (see Table 4). It is possible that the additional information provided by the paragraphs allowed the dyslexic group to adequately comprehend the text and to appear similar to the control group. This could explain the lack of differences between the groups, though additional study is needed to be sure of this. Future studies should implement single word or rapid serial visual presentation based paradigms as well as paragraph based text in order to draw direct comparisons between each method and determine the appropriate application of each paradigm.

**Why did the ROI analyses work?** A note must be said concerning the success of the ROI analyses. Despite a lack of differences in the whole brain analysis, the ROI analyses did reveal several regions to be associated with dyslexia. ROI based analyses offer a specific advantage compared to a whole-brain analysis, the minimization of statistical tests. Second level analyses are much less reliable compared to region of interest based analyses. ROI based analyses offer greater statistical control by minimizing the number of statistical tests performed and decreasing Type I error (Poldrack, 2007). Therefore, the results of the ROI analyses are much more robust than the group level results.

**BOLD Response in Regions of Interest**

**Left Temporal Lobe**

Activation within the left temporal lobe was found to have a negative association with dyslexia in both the *a priori* and *post-hoc* ROI analyses of the reading network. The left temporal lobe plays an important role as part of the ventral stream in reading, and activation is directly tied to reading ability (Noppeney, Price, Duncan, & Koepp, 2005),
therefore its relationship with dyslexia is not surprising. Structures in this region are
generally involved in the orthographic processing of text and integrating it with semantic
representations. Decreases in activation in this region is interesting and reflects impairment
in tying semantic knowledge with word orthography (the visual form of the word). This is
consistent with their sensitivity to lexical predictability. Decreases in lexical predictability
were associated with increased total dwell time (the sum of fixations upon a word during
the first pass and all subsequent passes through the word). This could be driven by an
inability to associate semantic knowledge with word orthography, driving the reader to
spend more time on that word during a trial in order to divine its meaning. Decreased
temporal activation could be a driver of this behavior, i.e. the lack of temporal activation
could indicate decreased retrieval, which could be due to decreased bottom-up input to
language and word specific cortical areas. This would impede orthographic processing.

This particular ROI was quite large as defined. It included much of the left
posterior middle temporal gyrus, left inferior temporal gyrus and left fusiform gyrus.
Therefore the BOLD response within this region includes functional regions such as the
visual word form area and fusiform face area. This is a rather wide net to cast and both of
these regions have been shown to be involved in linguistic processing. It is vital in follow
up studies to further segment this large region of interest into smaller functional regions.
This could be done via additional meta-analyses using Neurosynth (if using the same
dataset) or ideally a localizer task in a follow-up study. A localizer task would enable
researchers to find the exact location of each functional region for each participant,
allowing for greater precision for each participant.

**Left Temporal Pole**

The left temporal pole likewise had a lower activation in relation to dyslexia in the
reading contrast as well as in the lexical predictability contrast. Previously, this region has
been shown to be involved in accessing semantic information (Binder, Desai, Graves, &
ECOLOGICAL DYSLEXIA

Conant, 2009; Price, 2012, sensitive to semantic integration and semantic prediction in normal readers (Weber, Lau, Stillerman, & Kuperberg, 2016; Willems, Frank, Nijhof, Hagoort, & Van den Bosch, 2016). It has also been shown to be sensitive to lexical predictability in skilled readers (Carter, Foster, Muncy, & Luke, 2019). Willems et al. (2016) observed an association with word surprisal values, (a measure inversely correlated with predictability, i.e. the harder it is to predict a word the higher the surprisal value). As surprisal increased, temporal activation increased.

Additionally the temporal poles are thought to be associated with accessing syntactic information (J. R. Brennan, Stabler, Van Wagenen, Luh, & Hale, 2016; J. Brennan et al., 2012; Dronkers, Wilkins, Van Valin Jr, Redfern, & Jaeger, 2004; Henderson, Choi, Lowder, & Ferreira, 2016) and assimilating that information with semantic knowledge (Wilson et al., 2014). In a previous study on reading behavior (see Carter et al. (2019)), the left temporal pole demonstrated activity that was uniquely tuned to lexical predictability, rather than semantic or syntactic predictability and it is thought to be dedicated to integrating whole word morpho-syntactic information with specific rather than general semantic integration. This study found a negative association between dyslexia and the BOLD response to lexical predictability.

The reduction in activation as a result of dyslexia is interesting and again could indicate a reduction in input from bottom-up processes. This degraded input would result in reduced activation of this region. This could lead to impaired integration of semantic knowledge with word form and make it difficult to understand complex, unfamiliar or infrequent words. Such individuals would be highly reliant on predictable words when reading like this test group. This would also impair an individual’s ability to integrate semantic and syntactic information about the text, leading to increased confusion about what was being read. The dyslexia group did score lower on comprehension questions in the GORT-5 ($t(42.567) = 2.7248$, $p = 0.009298$). This contributed to lower sums of scaled scores for the GORT-5 (see Figure 2, Tables 2 and 3). It is likely this impaired
comprehension is a product of decreased activation of the left anterior temporal pole, and may be driven by decreased input to that region from other lower level processes.

**Left Supplementary Motor Area and Posterior Middle Frontal Gyrus**

This region of the brain has been reported as being central to the covert production of articulation (subvocalizing) (Martin, Schurz, Kronbichler, & Richlan, 2015), and the generation of eye movements (McDowell, Dyckman, Austin, & Clementz, 2008; Müri & Nyffeler, 2008). It has direct connections to oculomotor nuclei in the brainstem. Activity in this region is positively associated with increased saccade frequency, and usually increases with the cognitive load of the task (McDowell et al., 2008). This region has also been shown to be sensitive to text (Henderson, Choi, Luke, & Desai, 2015). More generally it appears to play a role in goal directed behavior. According to Stuphorn (2015), this region may be involved in learning context-dependent rules in order to predict the outcome of an oculomotor plan. In terms of a reading paradigm, the role of the SMA would be to integrate input from current and previous fixations to predict the outcome of a planned saccade. This would aid in the planning and execution of an effective reading behavior.

Lowered activation of this region is interesting in the setting of dyslexia. These individuals generally engage in longer fixations and shorter saccades. The SMA would be expected to have reduced activation as a result. In this study, we have also shown the oculomotor behavior of the dyslexia group to be highly dependent on lexical predictability. Considering with the finding that the SMA activation was associated with reduced activation in lexical predictability, one begins to see more evidence of a importance of and reliance on lexical predictability for the dyslexic reader.

**Right Inferior Occipital Lobe**

This particular region of interest covered a number of structures including the middle occipital gyrus, inferior occipital gyrus and lingual gyrus. Sakurai (2004) observed that lesions in this region seemed to impair tying word forms to phonology. Tan, Laird, Li,
and Fox (2005) likewise observed that it was associated with phonological processing. Cattinelli, Borghese, Gallucci, and Paulesu (2013) found this region to be associated with pseudoword reading via a meta-analysis, and proposed this was an early site for visually processing words. Overall, this region appears to be the first region to attempt to associate word form with phonology since it neighbors the primary visual cortex, thus it should be expected that impairment and dysfunction here is associated with greater difficulty in identifying novel words via phonological decoding. Likewise, we have also observed this region is negatively associated with lexical predictability (Carter et al., 2019), and therefore is more active as word predictability decreases. This would be expected as cognitive load increases when greater attention must be given to decipher it. It is not surprising that it should appear in this study.

This is not the first time this region has appeared in studies of dyslexia. B. A. Shaywitz et al. (2002) observed a decrease in activation relative to normal readers during the use of a semantic category judgement task. Our findings are similar in that paragraph reading is a highly semantic task, requiring the integration of the meaning of many different words into a single concept. Differences this early in the decoding process would certainly result in impaired integration with semantic knowledge at higher levels of cognition.

**Right Parahippocampal Gyrus and the Hippocampus**

The involvement of this region is interesting. This region was also reported by Cattinelli et al. (2013) in their meta-analysis. In that particular analysis it appeared as a non-specific cluster, meaning that it did not appear to be associated with any specific reading task and only appeared to be generally involved. Willems et al. (2016) noted the region appeared to respond to surprisal, meaning that it became more active as surprisal increased. This being the inverse of predictability, it is interesting to note it was also involved in this study, with activation being reduced in the dyslexic group. This particular
region is too far forward to be involved in early processing of orthographic or phonological representations of text. Rather, since it is sensitive to surprisal, it is possible this region’s reduced activity is due to decreased retrieval of semantic information during reading, relative to normal readers. This may play a role in the dyslexia test groups propensity to return to words after completing their first pass through. It could be the decreased activation in this region results in delayed word recognition, or integration of semantic and phonological information, thus driving a need to refixate upon it multiple times while reading. The reasons for this reduction in activity could be similar to those mentioned before, such as insufficient bottom-up input to correctly tie semantic and phonological information.

**The Cerebellum**

The cerebellum is not a structure one would think has a direct association with reading. However it is often activated in reading and reading related tasks (Stoodley & Stein, 2011). Mariën et al. (2014) proposed the cerebellum was central to the development of many processes supporting reading including fixation accuracy, hand-eye coordination, eye-voice coordination, sensori-motor-cognitive integration, speech internalisation, processing speed, verbal working memory, word recognition, and grapheme-phoneme isolation. Therefore it is not surprising this region appeared in as part of the meta-analyses for the reading and eye fields.

There is even a "cerebellar deficit" hypothesis which proposes the cerebellum contributes to the development of articulation and phonological ability and skill automatisation (Baddeley, 2003; Marvel & Desmond, 2010; Nicolson, Fawcett, & Dean, 2001). This would also result in deficits in procedural learning, which has also been observed (Pavlidou et al., 2010) with mixed success (Nigro, Jiménez-Fernández, Simpson, & Defior, 2016; Schmalz, Altoè, & Mulatti, 2017). Therefore it is not surprising cerebellar activation is negatively associated with dyslexia.
**Left Parietal Eye Fields**

The parietal eye fields are central to visual integration and attention. Their proximity allows them to influence attention allocation earlier than higher cortical regions. It’s primary role is control of the reflexive exploration of the visual environment, i.e. it controls whether or not saccades continue to be executed or if they are inhibited to allow the gaze to be focused on an item of interest (Müri & Nyffeler, 2008). A recent lesion study (Valdois, Lassus-Sangosse, Lallier, Moreaud, & Pisella, 2019) in a patient with bilateral loss of the parietal eye fields has raised the possibility that selective impairment of visual attention could lead to dyslexia without phonological impairment.

**Poor Input or Output?**

The overall findings of an increased sensitivity to lexical predictability, and reductions in the BOLD response relative to controls in the ROI analysis leads us to a question why this is the case. Is this phenomenon driven by bottom-up errors or top-down errors? Is the sensitivity to lexical predictability a result of poor input from poor attention or poor phonological and/or orthographic decoding? Or is this due to faulty prediction machinery? While this study cannot provide a definitive answer to these questions, some clues are present. For example, the overall depression in the bold response suggests a potential lack of stimulation to these regions relative to controls. This is consistent with a deficit in bottom up processing rather than a top-down etiology. Activation within one region of the cortex should be directly related to the degree of input received from other regions according to basic Hebbian theory (Hebb, 1949). Additionally, this depression of activity could indicate reading behavior is less goal oriented in dyslexia. Indeed, the frontal eye fields and supplementary eye fields are responsible for developing an oculomotor plan fitted to the objectives of the individual (Müri & Nyffeler, 2008). This would also explain the sensitivity to lexical predictability. Dyslexic readers may essentially be "along for the ride" when reading and without a definite strategy. A deficit in bottom-up information
would make it difficult to engage in goal oriented reading; one must have preliminary information about the text in order to decide how to read it. This lack may be leaving dyslexic readers unable to make effective oculomotor plans, leaving them at the mercy of the text rather than the masters of it.

More study is necessary to explore this idea – that there is a bottom-up deficit in dyslexia. Past studies have pointed towards potential causes such as a magnocellular deficit (D’Mello & Gabrieli, 2018; Stein, 2019). The magnocellular pathway is an important component of early visual processing beginning in the retina and extending through the thalamus to the visual cortex. This particular pathway is central to the allocation of visual attention, performing visual search tasks, determining the location of objects and their relation to each other. Pre-readers later diagnosed with dyslexia have been found to have deficits in recognizing individual letters (Ozernov-Palchik et al., n.d.) and sequencing them correctly (Howard Jr, Howard, Japikse, & Eden, 2006). The magnocellular pathway therefore is important for allocating visual attention in reading (Vidyasagar & Pammer, 2010). Such a lower level deficit could explain the lack of input to higher cortical centers in this study. Follow-up is needed to confirm this.

Next Steps

A few recommendations can be made based upon this study. First, studies using paragraph based stimuli in the study of reading need greater statistical power. Similar studies in readers used much larger sample sizes to study skilled readers (Carter et al., 2019; Choi, Lowder, Ferreira, Swaab, & Henderson, 2017; Henderson et al., 2016; Henderson et al., 2015) and even larger samples may be necessary to detect potentially subtle changes in dyslexia. Second, future studies of reading should include simplified readings tasks such as single or rapid visual presentation paradigms, in addition to paragraphs of text. This will enable researchers to draw specific conclusions concerning the effectiveness and application of each method in studying reading and dyslexia. Such tasks
also have the added benefit of serving as a localizer task for more targeted region of interest analyses. Third, individuals reporting a diagnosis of dyslexia are usually reliable in their reporting (at least in our sample population). This is supported by the preservation of the findings of the ROI analyses between the \textit{a priori} and \textit{post-hoc} analyses. However, it is still wise to independently administer cognitive tests for reading and phonological ability to ensure data integrity. Fourth, individuals with dyslexia appear to have an overall depression in the BOLD response in higher cortical regions. Finally, future studies should consider the possibility that deficits in bottom-up processes like the magnocellular pathway are the primary contributors to dyslexia and implement this into their experimental design. Stein (2019) describes several examples of experimental paradigms that could be used to this effect.

Conclusion

This study confirms findings of previous studies of dyslexia, i.e. that there are functional differences between dyslexic and otherwise normal individuals. The ROI analysis revealed that individuals with dyslexia had reduced activation compared to the control group. Word predictability was likewise associated with decreased total dwell time, implying that individuals with dyslexia are more reliant on word predictability than average readers in order to successfully decipher text. This is more evidence of a greater reliance on lexical predictability in dyslexia, however more study is needed to determine the cause—whether it is due to defective predictive machinery or whether this is due to degraded input. Given reduction in the BOLD response in all studied regions of interest, and the increased reliance on word predictability, it is proposed this is due to degraded input to the higher cortical centers and other regions engaged in prediction in dyslexia rather than defective predictions. A prime focus of future studies should include components of the magnocellular pathway as described by Stein (2019).
Figure 1
Regions of Interest and Gray Matter Mask

A. The eye fields. This includes the frontal eye fields, dorsolateral prefrontal cortex, parietal eye fields, supramarginal gyrus, visual cortex, cerebellum, and right putamen. B. The reading fields. This includes the left inferior frontal gyrus, left temporal pole, left inferior temporal gyrus, left fusiform gyrus, left parietal lobe, left posterior superior frontal gyrus, right parahippocampal gyrus, right fusiform gyrus, and right parietal lobe. C. Prediction fields. This primarily focused on the head of the caudate and part of the putamen. D. Whole brain mask. This mask was used to restrict the whole brain analysis to gray matter.
**Table 2**

*Cognitive test results*

<table>
<thead>
<tr>
<th>Test</th>
<th>Measure</th>
<th>Control</th>
<th>Dyslexia</th>
</tr>
</thead>
<tbody>
<tr>
<td>WASI-II</td>
<td>FSIQ-2</td>
<td>119.62 (8.8)</td>
<td>112.5 (6.47)</td>
</tr>
<tr>
<td>GORT-5</td>
<td>Sum of Scaled Scores</td>
<td>22.86 (2.03)</td>
<td>16.62 (3.06)</td>
</tr>
<tr>
<td>CTOPP</td>
<td>Phonological Awareness</td>
<td>114.43 (8.21)</td>
<td>107 (9.35)</td>
</tr>
<tr>
<td></td>
<td>Rapid Symbolic Naming</td>
<td>105.62 (11.28)</td>
<td>83.38 (17.29)</td>
</tr>
</tbody>
</table>

**Table 3**

*Student’s T-test results*

<table>
<thead>
<tr>
<th>Test</th>
<th>Measure</th>
<th>T-statistic</th>
<th>Degrees of Freedom</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>WASI-II</td>
<td>FSIQ-2</td>
<td>3.055</td>
<td>36.32</td>
<td>0.0042</td>
</tr>
<tr>
<td>GORT-5</td>
<td>Sum of Scaled Scores</td>
<td>8.133</td>
<td>40.25</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>CTOPP</td>
<td>Phonological Awareness</td>
<td>2.839</td>
<td>43.00</td>
<td>0.0069</td>
</tr>
<tr>
<td></td>
<td>Rapid Symbolic Naming</td>
<td>5.170</td>
<td>39.95</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

**Table 4**

*Oculomotor profiles*

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Control</th>
<th>Dyslexia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>First fixation duration</td>
<td>215.52 (92.01)</td>
<td>255.46 (144.05)</td>
</tr>
<tr>
<td>First run dwell time</td>
<td>244.13 (123.85)</td>
<td>324.92 (217.96)</td>
</tr>
<tr>
<td>Total dwell time</td>
<td>287.09 (180.24)</td>
<td>392.06 (273.75)</td>
</tr>
<tr>
<td>Refixation probability</td>
<td>0.28 (0.08)</td>
<td>0.34 (0.11)</td>
</tr>
</tbody>
</table>

**Table 5**

*Significance of group differences*

<table>
<thead>
<tr>
<th>Statistic</th>
<th>T-statistic</th>
<th>Degrees of Freedom</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean first fixation duration</td>
<td>-5.030</td>
<td>42.97</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean first run dwell time</td>
<td>-5.291</td>
<td>38.75</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean total dwell time</td>
<td>-6.116</td>
<td>37.32</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Refixation probability</td>
<td>-5.532</td>
<td>42.46</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

**Table 6**

*First fixation*

<table>
<thead>
<tr>
<th>Estimate</th>
<th>Std. Error</th>
<th>Degrees of Freedom</th>
<th>T-statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>5.286</td>
<td>43.59</td>
<td>268.411</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Dyslexia</td>
<td>0.149</td>
<td>43.87</td>
<td>5.579</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Lexical Pred.</td>
<td>-0.001</td>
<td>33482.83</td>
<td>-0.481</td>
<td>0.631</td>
</tr>
<tr>
<td>Dyslexia * Lexical Pred.</td>
<td>0.000</td>
<td>33485.38</td>
<td>0.010</td>
<td>0.992</td>
</tr>
</tbody>
</table>
Figure 2
Distribution of cognitive test scores

Distribution of the scores by group for the (A) Full Scale IQ-2 (WASI-II), (B) Sum of Scaled Scores (GORT-5), (C) Phonological Awareness (CTOPP-2), and (D) Rapid Symbolic Naming (CTOPP-2).
**Figure 3**
*Whole brain response to paragraphs by group.*

Whole brain responses to text by group: *A*. Control group. *B*. Dyslexia group. Voxelwise threshold \( p < 0.001 \), cluster threshold = 39 voxels, nearest neighbors = 1, overall \( \alpha < 0.05 \).

**Table 7**
*First run dwell time*

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>Std. Error</th>
<th>Degrees of Freedom</th>
<th>T-statistic</th>
<th>( p )-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>5.392</td>
<td>0.021</td>
<td>43.56</td>
<td>250.796</td>
<td>( p &lt; 0.0001 )</td>
</tr>
<tr>
<td>Dyslexia</td>
<td>0.232</td>
<td>0.029</td>
<td>43.88</td>
<td>7.947</td>
<td>( p &lt; 0.0001 )</td>
</tr>
<tr>
<td>Lexical Pred.</td>
<td>-0.005</td>
<td>0.002</td>
<td>33486.63</td>
<td>-3.540</td>
<td>( p &lt; 0.0001 )</td>
</tr>
</tbody>
</table>

**Table 8**
*Total dwell time*

<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>Std. Error</th>
<th>Degrees of Freedom</th>
<th>T-statistic</th>
<th>( p )-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>5.520</td>
<td>0.023</td>
<td>43.41</td>
<td>241.43</td>
<td>( p &lt; 0.0001 )</td>
</tr>
<tr>
<td>Dyslexia</td>
<td>0.274</td>
<td>0.031</td>
<td>43.75</td>
<td>8.82</td>
<td>( p &lt; 0.0001 )</td>
</tr>
<tr>
<td>Lexical Pred.</td>
<td>-0.006</td>
<td>0.002</td>
<td>33482.89</td>
<td>-2.64</td>
<td>0.008</td>
</tr>
<tr>
<td>Dyslexia * Lexical Pred.</td>
<td>-0.010</td>
<td>0.003</td>
<td>33485.94</td>
<td>-2.88</td>
<td>0.004</td>
</tr>
</tbody>
</table>
Figure 4
The effect of group and lexical predictability on first fixation duration

Table 9
Intercorrelations of cognitive subtest scores

<table>
<thead>
<tr>
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<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Fluency (GORT-5)</td>
<td>1.00</td>
<td>0.44</td>
<td>0.44</td>
<td>0.58</td>
</tr>
<tr>
<td>2. Comprehension (GORT-5)</td>
<td>0.44</td>
<td>1.00</td>
<td>0.45</td>
<td>0.02</td>
</tr>
<tr>
<td>3. Phonological Awareness (CTOPP-2)</td>
<td>0.44</td>
<td>0.45</td>
<td>1.00</td>
<td>0.26</td>
</tr>
<tr>
<td>4. Rapid Symbolic Naming (CTOPP-2)</td>
<td>0.58</td>
<td>0.02</td>
<td>0.26</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Figure 5
The effect of group and lexical predictability on first run dwell time

Table 10
Factor loadings from Principle Components Analysis

<table>
<thead>
<tr>
<th></th>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>Factor 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluency</td>
<td>-0.595</td>
<td>0.199</td>
<td>-0.363</td>
<td>0.689</td>
</tr>
<tr>
<td>Comprehension</td>
<td>-0.448</td>
<td>-0.619</td>
<td>-0.461</td>
<td>-0.451</td>
</tr>
<tr>
<td>Phonological Awareness</td>
<td>-0.510</td>
<td>-0.283</td>
<td>0.809</td>
<td></td>
</tr>
<tr>
<td>Rapid Symbolic Naming</td>
<td>-0.430</td>
<td>0.705</td>
<td>-0.563</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6
The effect of group and lexical predictability on total dwell time

Table 11
Changes in group assignment from factor analysis

<table>
<thead>
<tr>
<th>Assignment by factor</th>
<th>Assignment by diagnosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Dyslexia</td>
</tr>
<tr>
<td>Control</td>
<td>4</td>
</tr>
<tr>
<td>Dyslexia</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>21</td>
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</table>
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