Eye Movements of Dyslexic and Average Readers in Meaningful and Pseudoword Passage Reading

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Abstract

Phonological processing deficits are at the core of reading failure from the early stages of reading into adulthood. One of the major consequences of these deficits is difficulty in pseudoword reading and phonological decoding. We investigated the effects of reading pseudowords in text on the eye movement behavior of adult readers with and without dyslexia. For both groups there were more fixations and regressions and longer fixation durations when reading passages with pseudowords than when reading passages without pseudowords. Readers with dyslexia made more fixations and regressions and longer fixations in both types of passages compared to typically achieving adult readers. The effects of the pseudoword passages were stronger for the participants with dyslexia than for those without dyslexia. These findings are consistent with the view that readers with dyslexia have not automatized the rapid activation and integration of phonological codes for orthographic stimuli, resulting in reliance on a serial decoding strategy during the reading of pseudowords in passages. These results document the challenges that students with dyslexia encounter when reading even simple texts.

Keywords: Phonological processing, pseudowords, dyslexia, adults, eye movements

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Phonological processing deficits are at the core of reading failure from the early stages of reading into adulthood (Castles et al., 2018). The phonological deficit theory of dyslexia proposes that dyslexia is caused by a deficit in the consolidation and/or retrieval of phonological or sound-based codes (Goswami, 2015; Hornickel & Kraus, 2013; Melby-Lervåg et al., 2012; Ramus, 2003, 2014; Ramus et al., 2013; Vellutino et al., 2004; Ziegler & Goswami, 2005). Phonological deficits are argued to impede the acquisition of alphabetic knowledge and decoding which then affects the succession of development in word recognition, fluent reading, and comprehension and leads to inaccurate and slow reading of texts (Bryant et al., 2014; Cardoso-Martins & Pennington, 2004). Phonological deficits have also been found to impede individuals' ability to read new verbal material such as unfamiliar words or pseudowords (pronounceable nonwords) (see, e.g., Nagy et al., 2006).

These behavioral phonological deficits are also reflected by differences at the neural level between readers with and without dyslexia (Al Dahhan et al., 2020). The left-hemisphere dominant neural reading network consists of temporoparietal, occipitotemporal, and inferior frontal areas (Al Dahhan et al., 2020; Cummine et al., 2014; Misra et al., 2004; Norton et al., 2015; Price & Mechelli, 2005; Shaywitz & Shaywitz, 2008). This reading network includes a ventral stream, which recognizes whole words and their meanings, dorsal stream, which links orthographic information to sublexical phonological representations, and a (Cohen et al., 2008; Price, 2012; Pugh et al., 2001). The ventral stream transmits information ventro-laterally and anteriorly and encompasses the inferior occipitotemporal regions, fusiform gyrus, and the middle temporal gyrus; the dorsal stream moves anteriorly from the visual cortex towards the parietal lobe and frontal regions and consists of the angular gyrus, superior temporal gyrus, and supramarginal gyrus (Borowsky et al., 2006; Pugh et al., 2000).

As children develop reading skills, there is a gradual increase in brain activity during reading within the left-hemisphere reading network and a decrease in activity in right hemisphere areas involved in visual memory (Turkeltaub et al., 2003). Within this left-hemisphere reading network, skilled readers have greater brain activity in the occipitotemporal regions, which is responsible for the automatic and fluent identification of visually presented words (Norton & Wolf, 2012; Shaywitz et al., 2006). However, for readers with dyslexia, the functioning of this posterior reading system is disrupted which may attribute to why they cannot fluently and automatically recognize words (Dehaene et al., 2005). Lower brain activation in the dorsal temporoparietal system compared to typical readers may indicate deficits in phonological processing, specifically in forming grapheme-phoneme associations, and the hypoactivation found in the ventral occipitotemporal system may reflect a secondary impairment in automatic visual word recognition (Richlan et al., 2011). Researchers have argued that an increased reliance on the inferior frontal regions of the reading network and posterior regions of the right hemisphere compensates for this functional disruption (Norton et al., 2015; Price & Mechelli, 2005; Richlan et al., 2011; Shaywitz & Shaywitz, 2006).

Although the left-hemisphere reading network has been identified in previous research, it is unclear how the reading network differs during the reading of pseudoword and phonological decoding in readers with and without dyslexia. Furthermore, the effects of reading pseudowords and phonological decoding have been most often studied behaviourally in children, even though adults with dyslexia also experience deficits in pseudoword decoding. These deficits are especially evident for university students with dyslexia who have to read many unfamiliar words while studying; unfamiliar words are essentially like pseudowords, their pronunciation must be assembled slowly and effortfully, as they cannot be recognized directly.

To address these important knowledge gaps in the literature, the goal of this study is to examine the effects of inserting pseudowords into meaningful texts on the eye movements of adult readers with and without dyslexia. Eye movement recording is a key tool for uncovering and understanding the cognitive and perceptual skills that are involved in the reading process in typical readers, with the variability that occurs in these eye movement measures is a reflection of the variability that occurs in on-line processing (Franzen et al., 2021; Razuk et al., 2018; Nilsson Benfatto et al., 2016). Therefore, eye movement recording may be a useful tool to studying the underlying cognitive processes that are involved during pseudoword tasks.

During reading, eye movements have three primary characteristics. First, there is a series of eye movements, or saccades, in which the eyes move very rapidly. Second, these saccades are separated by periods of time in which the eyes are relatively still, called fixations. Due to the high velocity of the saccade, no useful information is acquired when the eyes are moving; readers only acquire information from the text during the fixations (Rayner & Clifton, 2009). Third, 10-15% of the time readers move their eyes back in the text to look at material that has already been read – these are named regressions. Regressions are thought to be due to problems in comprehending the material, making too large forward saccades, lack of semantic control, or inference making (Rayner et al., 2004; Olitsky & Nelson, 2003).

Eye movement studies with typically-developing readers have shown a developmental trend as reading skill increases and faster information processing occurs: fixation duration decreases, saccade length increases, and the frequency of regressions decreases (Olitsky & Nelson, 2003). The most marked changes occur between beginner readers and readers who are in third or fourth grade: when children have had four years of reading experience, their eye movements are not too different from those of adults - the only exception being that the frequency of regressions is greater for children than for adults (Rayner et al., 2006). Conversely, as the difficulty of text increases, fixation duration increases, saccade length decreases, and regression frequency increases. Thus the variability in fixation time and saccade length that occurs between readers, and even within readers, has been thought to be related to cognitive processes that are associated with word recognition and comprehension (Rayner, 2009).

Compared to average readers, readers with dyslexia have been found to make longer and more fixations, shorter saccades, and more regressions (e.g., Razuk et al., 2018; Nilsson Benfatto et al., 2016; Seassau et al., 2014; Bucci et al., 2012; Jainta & Kapoula, 2011; Hutzler & Wimmer, 2004). However, despite these established group differences in eye movement behavior between readers with and without dyslexia, the specific role and contribution of aberrant eye movement behavior is not established in the literature (Stein et al., 2018; Blythe et al., 2018; Quercia et al., 2013). These findings have led to three hypotheses to explain the differences in eye movements between these two groups. First, dyslexics' eye movements are a reflection of the problems that they have with the reading material; in other words, as they become more confused, their eye movements become more erratic. Second, erratic eye movements may sometimes be the cause of dyslexia. Third, erratic eye movements are the symptoms of one or more commonly shared or independent but parallel central deficits for readers with dyslexia. More research needs to be conducted to determine which, if any, of these three theories accurately explains the atypical eye movements that are observed in readers with dyslexia. It is also important to note that eye movements do not provide direct evidence of decoding; however, readers engaging in effortful decoding will make eye movements as they decode successive units. A reader decoding syllable-by-syllable should make fewer eye movements than one decoding grapheme-by-grapheme, which suggests that eye movements are a plausible index of effortful reading (Castles et al., 2018). Pseudoword passages were used in the present study instead of pseudoword lists due to the precise oculomotor control (voluntary and purposeful eye movements) that is required in reading continuous text, and aberrant eye movements and fixations (length of time spent maintaining gaze on a specific location) have been found to differentiate between average readers and readers with dyslexia (Al Dahhan et al., 2014; Stein, 2018).

Research has reported an inefficiency of phonological code activation in students with dyslexia (e.g., Cao et al., 2006; Cavalli et al., 2017; Hutzler & Wimmer, 2004; Navas et al., 2014). However, in adulthood it is difficult to study the effects phonological processing deficits have on pseudoword reading and phonological decoding because participants' extensive reading experience and print exposure allow them to utilize orthographic skills to compensate for deficiencies in phonological skills when dealing with familiar words (Majeres, 2005; Parrila et al., 2007). To account for this, pseudoword decoding tasks have been used to tap into phonological skills because knowledge of spelling-sound correspondences is necessary to decode pseudowords and pseudowords cannot be recognized by whole-word orthographic processes (Bowey & Muller, 2005; Castles et al., 2018). Pseudowords are pronounceable and are composed of letters and syllables that may be recognized as units. Therefore, pseudowords in real text may resemble what adult readers encounter while reading unfamiliar words, proper names, and/or technical terms as there is no fundamental difference between an unfamiliar word and a pronounceable pseudoword (De Luca et al., 2002).

Our first research question is what effect the presence of pseudowords in passages has on eye movement behavior. Eye movements are influenced by many variables including text difficulty, word frequency, and word predictability (Drieghe et al., 2005; Rayner et al., 2004; Reingold & Rayner, 2006; Kuperman et al., 2018). For typically-developing readers, as text difficulty increases, fixation duration increases, saccade length (movement of gaze from one position to another) decreases, and frequency of backwards saccades (regressions) increases (Rayner, 2009). In reading pseudowords, attention needs to be given to smaller units, such as syllables, onsets, rhymes, and letters, whereas many real words can be easily recognized as single units (Castles et al., 2018). This difference in attentional requirements suggests that saccadic patterns in reading pseudowords and real words should differ, if the real words are familiar.

Most existing eye movement research has investigated the effect of single encounters of pseudowords on eye movements (e.g., Chaffin et al., 2001; De Luca et al., 2002; Hutzler & Wimmer, 2004; Lowell & Morris, 2014; Wochna & Juhasz, 2013). This line of work has found that readers with and without dyslexia make longer and more fixations and more regressions when reading lists of pseudowords compared to reading meaningful words (De Luca et al., 2002; Hutzler & Wimmer, 2004). Furthermore, while there are no effects of pseudowords on fixation location, greater processing times and re-fixations have been found when naming pseudowords compared to familiar words (Lowell & Morris, 2014). These findings are consistent with studies that have found a word frequency effect on eye movements and indicates that pseudowords may be processed similarly to the processing of low-frequency words (Rau et al., 2015). For example, typical readers have been found to use larger orthographic units during pseudoword decoding, compared to readers with dyslexia who used a letter-based decoding approach (Hautala et al., 2012). However, it has not yet been determined whether these pseudoword lists findings are similar for pseudoword passage reading in adult readers. We hypothesize that there will be a greater number of fixations and regressions, and longer fixation durations when reading pseudoword passages than when reading meaningful passages.

Our second research question is whether there are differences in eye movement performance between typically achieving adult readers and readers with dyslexia during meaningful and pseudoword passages. There is likely an inter-relationship between pseudoword reading competency, reading ability, and eye movement patterns. When comparing average readers to readers with dyslexia, there are differences in reading speed, reading accuracy, and eye movement performance while reading pseudowords and real words. Individuals with dyslexia perform at a much lower level than average reading individuals on pseudoword decoding, and the phonological skills necessary for these tasks do not reach average levels into adulthood (Miller-Shaul, 2005). This is supported by findings that readers with dyslexia are slower and less accurate (Castles et al., 2018), and make longer and more fixations and regressions and shorter saccades (Hawelka et al., 2010; Hawelka & Wimmer, 2005) during word, pseudoword, and sentence reading than average readers.

Readers with dyslexia with poor decoding skills tend to use a serial decoding strategy to break words down into smaller subunits when reading real words and pseudowords compared to average readers (Coltheart et al., 2001; Hutzler & Wimmer, 2004). Furthermore, this serial decoding strategy suggests that readers with dyslexia read real words in a way similar to that in which typically achieving readers read pseudowords. Therefore, based on these findings we hypothesize that we will find longer and more fixations and regressions in both types of passages for readers with dyslexia compared to typically achieving adult readers, but the magnitude of these effects are unknown.

Materials and Methods

Participants

All participants were undergraduate students, ranging from 19-23 years old, whose predominant language was English. All participants had been accepted into a selective university, suggesting high levels of high school achievement and average to above average SES. Participants were in two groups: 20 students with dyslexia (9 males, 11 female) and 37 students with no known history of reading disability (termed typically achieving) (10 males, 27 female). Descriptive statistics for raw scores on measures of reading and decoding ability (described in the next section) are presented in Table 1. In terms of the reading and decoding tests' norms, scores for typically achieving participants were equivalent to two standard deviations above the norm for 19-23 year olds, whereas the readers with dyslexia performed below the norm. In terms of the typically achieving group's distributions, the differences between the groups were approximately one to three standard deviations. Participants with dyslexia had current psycho-educational documentation and had their diagnosis affirmed by a clinical psychologist. A power calculation based on the effect size of 1.58 found by Hutzler and Wimmer (2004) indicated groups of 10 participants would be sufficient to detect such an effect. All experimental procedures were approved by the [blinded] University Research and Ethics Board and complied with the principles of the Canadian Tri-council Policy Statement on Ethical Conduct for Research Involving Humans and the principles of the Declaration of Helsinki (1964). All participants gave their written and informed consent prior to testing.

Measures of Reading and Decoding Ability

Measures of reading and decoding ability were administered to confirm and validate the differences in reading ability between groups.

Word Recognition. Untimed and timed single word reading were measured. Untimed single word reading was assessed using the Woodcock Word Identification test (Woodcock, 1998), in which participants were asked to read aloud up to 106 words that increased in difficulty until they either attempted all the words or made six consecutive errors. Participants' scores were the number of words read correctly. The college student split-half reliability for this test is .94 (Woodcock, 1998). Timed single word reading was assessed using the Sight Word Efficiency (Wagner et al., 1999) test in which participants were asked to read aloud as quickly as possible a list of 104 words that increased in difficulty. An eight-word practice list was presented before the test. Participants' scores were the number of words read correctly within the 45-s time limit. The age-19-and-above test-retest reliability estimate for this test is in the range of .82 to .87 (Torgesen et al., 1999).

Reading Comprehension. The Nelson-Denny Reading Comprehension test (Form G; Brown et al., 1993) has a 20-minute time limit. Participants were asked to read seven passages and answer multiple-choice questions after each passage. The comprehension score was the number of multiple-choice questions that participants answered correctly (KR-20 reliability estimates of .81; Smith & Plake, 1998).

Reading Rate. Reading rate was measured with the first passage on the Nelson-Denny Reading Comprehension test (Form G; Brown et al., 1993). The score indicates how many words the participant had read after one minute.

***Decoding Ability*.** Participants' decoding ability was assessed with untimed and timed measures. Untimed decoding skills were assessed using the Woodcock Word Attack test (Woodcock, 1998), in which students were asked to read aloud up to 45 pseudowords that increased in difficulty until they either attempted all the words or made six consecutive errors. Participants' scores were the number of pseudowords read correctly. The college student split-half reliability for this test is .81 (Woodcock, 1998). Timed decoding skills were assessed using the Phonemic Decoding Efficiency test (Wagner et al., 1999) in which participants were asked to read as fast as possible a list of 63 pseudowords that increased in difficulty. An eight-word practice list was presented before the test. Participants' scores were the number of pseudowords read correctly within the 45-s time limit. The age-19-and-above test-retest reliability estimate for this test ranges from .91 to .94 (Torgesen et al., 1999).

Passage Reading

There were four reading passages written specifically for this study: one pair of passages about shopping (63 words, one meaningful and one pseudoword passage) and one pair about wine (61 words) (Figure 1). Pseudoword passages were derived from the meaningful passages. Fifteen content words from each meaningful passage were replaced with pseudowords; all function words remained unchanged. The same pseudowords were used in each passage. Pseudowords were constructed from the ARC Nonword Database (Rastle et al., 2002) and were matched in number of syllables and letters to the words they replaced. The passages were at the grade 8 to 9 reading level (Fry, 1977). Prior to the presentation of the tasks, a practice passage with one pseudoword was presented to participants to ensure an adequate understanding of the task.

Readers with dyslexia and typically achieving readers were randomly assigned to four groups: (a) wine meaningful passage first, shopping pseudoword passage second; (b) wine pseudoword first, shopping meaningful second; (c) shopping meaningful first, wine pseudoword second; and (d) shopping pseudoword first, wine meaningful second.

Participants were instructed to read aloud the passages to ensure they were reading each word. Errors made during passage reading were not recorded because we were interested in the overall effects these passages had on eye movement performance rather than the accuracy of word reading.

Eye-Tracking and Visual Display

Eye position was recorded using the Eyelink II eye tracking system (SR Research Ltd, Mississauga, ON). Passages were displayed on a 17" computer monitor with a resolution of 640 by 480 pixels at a frame rate of 120 Hz. To maintain spatial uniformity between the meaningful words and pseudowords in the passages, a monospaced GulimChe font in size 18 was used. All recordings and calibrations were done monocularly, viewing of the display was binocular. The position of the left pupil was digitized in both the vertical and horizontal axes at a sampling rate of 250 Hz and average gaze position error of <0.5°. Before administration of the passages, eye position was calibrated using nine randomly timed targets on the screen (eight around the periphery and one central). The targets were flashed sequentially around the screen and the participant fixated on each one. After calibration, the process was repeated one more time to validate that the average error between fixation and target was < 2° and that no loss of eye tracking occurred.

The number of fixations, number of regressions, and fixation durations were computed for all participants. Oculomotor pauses between saccades were recorded as fixations, and a saccade was defined as an eye movement greater than 0.15° of visual angle. Fixation durations are generally greater than 50 ms (Rayner, 2009). Therefore, only fixations with durations greater than 50 ms were considered in the final analyses. Regressions were defined as leftward saccades that were within 30° of visual angle in the horizontal and were less than 10° in amplitude (so as to omit blinks and eye movements to fixate upon the next line of text). To simplify the results presented in this paper, we present eye movement patterns at the paragraph level and examine globally how these patterns change over the course of the display. Future studies should analyze the eye movement data at the individual item level to examine how these patterns are affected by bigram and trigram frequencies.

Procedure

Participants were tested individually in two sessions. In the first session, participants were randomly assigned to one of four conditions: (a) Meaningful wine passage followed by the pseudoword version, (b) pseudoword version of the wine passage followed by the meaningful version, (c) meaningful shopping passage followed by the pseudoword version, or (d) pseudoword version of the shopping passage followed by the meaningful version. This design ensured that practice effects were kept at a minimum, as the similarities between meaningful wine passage and its pseudoword version and the similarities between meaningful shopping passage and its pseudoword version would have been salient. The design also ensured that the orders of passage type (meaningful, pseudoword) and passage topic (wine, shopping) were counterbalanced. After reading of the first passage was complete, the second passage was presented, and the participant read this passage out loud as their eye movements were recorded. In the second session the reading ability tests were administered. Upon completion of the study, participants received either course credit or a $20 honorarium for their time.

Results

Differences in Reading Ability

Descriptive statistics for the reading ability measures are presented in Table 1 for each group. A MANOVA revealed a main effect of group, Wilks' $\lambda = .46$, $F(1, 54) = 9.50$, $p < .001$. Subsequent univariate ANOVAs showed that the typically achieving readers performed significantly better than the adults with dyslexia on each reading and decoding ability measure (Table 1). This is to be expected because dyslexia is argued to impede the acquisition of alphabetic knowledge and decoding, which in turn affects the succession of development in word recognition, fluent reading, and comprehension (Misra et al., 2004). These results confirm that there was a substantial difference in a range of reading ability measures between the two groups of university students.

Differences in Eye Movements Between Readers With and Without Dyslexia

Descriptive statistics for the eye movement measures in meaningful and pseudoword passage reading are shown in Table 2 by group. Three 2 (Group: Typically Achieving, Dyslexic) x 2 (Passage Type: Meaningful, Pseudoword) ANOVAs with repeated measures on the second factor were used to examine the effects on number of fixations, number of regressions, and fixation duration.

The Group effects showed that readers with dyslexia made more fixations, $F(1, 55) = 57.82$, $p < .001$, $g = .63$, and regressions, $F(1, 55) = 33.78$, $p < .001$, $g = .49$, but the groups did not differ on fixation duration, $F(1, 55) = .98$, $p = .33$, $g = .06$. Similar results were found after controlling for the effect of topic order and passage order.

The Passage Type effect was significant for each outcome: number of fixations, $F(1, 55) = 93.12$, $p < .001$, $g = .56$, number of regressions, $F(1, 55) = 52.77$, $p < .001$, $g = .39$, and fixation duration, $F(1, 55) = 69.70$, $p < .001$, $g = .49$. There were more fixations, more regressions, and longer fixation durations in pseudoword than in meaningful passage reading. The Passage Type x Group interaction (Figure 2) was significant for each outcome: number of fixations, $F(1, 55) = 22.47$, $p < .001$, $g = .27$, number of regressions, $F(1, 55) = 17.96$, $p < .001$, $g = .23$, and fixation duration, $F(1, 55) = 4.43$, $p < .05$, $g = .07$. Readers with dyslexia displayed a larger discrepancy in eye movements between meaningful word reading and pseudoword reading compared to typically achieving participants. The difference in the number of fixations between real word and pseudoword passages was about 3 times larger for the readers with dyslexia than for normal readers; the difference in the number of regressions was more than 11 times greater for the reading disabled group compared to controls; and the difference in fixation duration was more the 1.5 times greater for the readers with dyslexia than for the typically achieving controls. Similar results were found after controlling for the effect of topic order and passage order.

Discussion

The aim of this study was to observe the effects of pseudowords in text on the eye movement behavior of adult readers with dyslexia. We first confirmed the difference in reading ability between the groups on a range of reading measures (Table 1). Results of the analyses of eye movement behavior were consistent with all hypotheses: fixation durations, number of fixations, and regressions were greater for both groups while reading passages that contained pseudowords, and these effects were exaggerated for readers with dyslexia compared with typically achieving readers (Table 2, Figure 2). These results extend earlier findings (Chaffin et al., 2001; De Luca et al., 2002; Hutzler & Wimmer, 2004; Lowell & Morris, 2014; Wochna & Juhasz, 2013) and indicate that conclusions about performance during pseudoword list reading in children with and without dyslexia are also valid for performance during pseudoword passage reading by adult readers with and without dyslexia.

Differences Between Readers With and Without Dyslexia

University students with dyslexia are likely to be compensated dyslexics (Parrila et al., 2007), and therefore have developed strategies to deal with regular text. Reading pseudoword passages may be especially difficult for university students with dyslexia because they have to switch back and forth between phonetic decoding of pseudowords and whatever other strategy they normally use. If that strategy involves searching for meaningful cues, it may lead them to make frequent regressions looking for hints about how to decode the pseudowords as a strategy to help compensate for their reading difficulties, which may also be more difficult for readers with dyslexia than typically achieving readers because of their deficient phonological skills (Parrila et al., 2007; Majeres, 2005).

Each of the three eye movement variables that were analyzed supports the phonological deficit hypothesis and provides an indication of the difficulties the students with dyslexia have. Whereas typically achieving students had a modest increase of about 30 fixations between the meaningful and pseudoword passages (about two of their meaningful passage standard deviations), the readers with dyslexia increased by about 85 (about four of their SDs). This suggests that the readers with dyslexia were working at a much smaller grain size (Ziegler & Goswami, 2005). Typically achieving readers may be able to recognize syllables in pseudowords automatically, but those with dyslexia appear to struggle letter by letter. The greater increase in regressions suggests either a search for clues, or less ability to control eye movements under challenging situations (Al Dahhan et al., 2017). Although the increase in fixation duration due to the pseudowords is not as striking (46 ms by readers with dyslexia as opposed to 28 ms by typically achieving readers), it demonstrates that more time was required to extract information from the stimuli during each fixation. Therefore, even if the students with dyslexia were fixating on smaller units (as suggested by the number of fixations), they were taking longer to extract information during each fixation. Overall the results support previous research and underline the inefficiency of phonological code activation in the students with dyslexia (e.g., Cao et al., 2006; Cavalli et al., 2017; Hutzler & Wimmer, 2004; Navas et al., 2014).

Effect of Pseudoword Passages on Eye Movements

The texts that university students are required to read are replete with unfamiliar words, including technical terms, foreign words, and surnames. If readers with dyslexia engage in letter by letter decoding and make many inefficient regressions, this will tax working memory resources and make comprehension more difficult; this in turn will undermine motivation to continue reading. The present results illustrate this effect with passages written at the middle school level; they may be even stronger with higher level texts. Efforts need to be made to alleviate these effects. It is unlikely that phonological or phonetic training will have much effect for this age group; it may be more effective to make separate lists of technical terms and definitions for each text. A further possibility is to engage students in morphological processing to encourage them to work at a larger grain size; morphology appears to be an area of relative strength for readers with dyslexia (Deacon et al., 2008; Kotzer et al., 2021) and can be used to compensate for phonological weaknesses (Law et al., 2015). Morphological instruction is also effective with less able readers (Bowers et al., 2010).

Although pseudoword reading has long been seen as the area of greatest difficulty for those with dyslexia (see, e.g., Nagy et al., 2006), this has been challenged by others who argue that dyslexics' reading of pseudowords is consistent with their general reading ability. The latter group has proposed instead that dyslexics' fundamental weakness is in establishing links between orthographic input and phonological codes (see Ramus, 2003, for a review). This issue is beyond the scope of the present paper, but the present results document how difficult it is for university students with dyslexia to read when encountering unfamiliar orthographic stimuli.

Several limitations of the current study should be mentioned. First, the participants in this study were young adults who were attending university and were likely not representative of all adult readers. Additionally, demographic data on participant's race/ethnicity, age, undergraduate level, and GPA were not collected in this study. Future studies should examine the role that these specific demographic measures play in eye movement behavior during these passages with a larger sample. Second, due to the pronounceable non-word nature of pseudowords, the non-authenticity of the passages may constrain the normal reading processes of those with dyslexia. To address this, future studies should investigate whether similar results are found during meaningful passage reading with unfamiliar real words rather than pseudowords. Furthermore, assessing eye movement performance at the passage level creates a limitation to examining group differences which requires future studies to examine the effect of pseudoword reading at the level of individual words. Third, despite the tester observing participants' behavior as they were going through the passages to ensure that they were on track, error data were not collected. However, as mentioned earlier, while eye movement behavior does not guarantee decoding behavior, decoding does influence eye movement behavior. Lastly, utilizing a readability formula (i.e., Fry, 1977) to estimate grade levels and difficulty of reading materials has limitations. For example, readability formulas have been found to be poorly correlated with oral reading fluency measures (Compton et al., 2004) and are not precise enough to be able to determine comparable assessment measures (Ardoin et al., 2005; 2010). However, researchers have used readability formulas to control for general text difficulty (e.g., Hintze & Christ, 2004) and found that passages from the same grade level were highly correlated with one another even though they could not be considered comparable to one another because they were not at the same difficulty level (Francis et al., 2008). Despite these limitations, the present study quantifies the difficulty that students with dyslexia face in reading text with unfamiliar words. Further refinements to the texts and measures deserve to be studied, but the greatest need is to design interventions to mitigate these difficulties.

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Table 1

Means and standard deviations of reading ability scores in typically achieving and dyslexic groups.

Measures	Typically Achieving $n = 37$		Dyslexic $n = 20$			
	M	*SD*	*M*	*SD*	$F(1,56)$	*g*
Nelson-Denny Reading Comprehension	31.24	4.85	24.90	9.34	11.29**	.85
Nelson-Denny Reading Speed	262.03	103.69	171.65	86.49	10.94*	.94
TOWRE Sight Word Efficiency	95.16	9.64	73.75	18.43	32.02**	1.45
TOWRE Phonetic Decoding Efficiency	56.62	7.27	36.40	13.85	50.67**	1.82
Word Attack	39.24	3.46	34.35	6.79	12.32**	.91
Word Identification	98.81	3.32	93.15	8.64	11.95**	.86

Note. * $p < .01$; ** $p < .001$.

Table 2

Means and standard deviations of eye movement measures in meaningful and pseudoword passages by reading group.

Measures	Typically Achieving *n* = 37		Dyslexic *n* = 20	
	M	*SD*	*M*	*SD*
Meaningful Passage				
Number of Fixations	80.22	15.74	107.05	21.22
Number of Regressions	23.05	7.10	34.60	10.84
Fixation Duration (ms)	220.97	26.31	223.37	51.82
Pseudoword Passage				
Number of Fixations	109.73	18.17	193.55	71.76
Number of Regressions	31.95	9.23	68.40	39.45
Fixation Duration (ms)	248.67	32.90	269.75	77.43

Figure 1

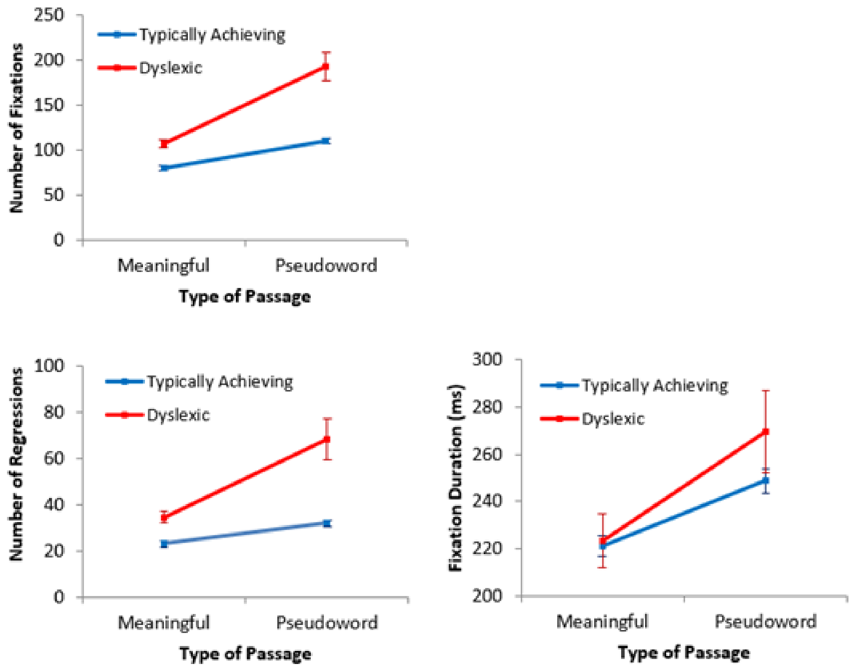
Passages used in the study.

Wine Passages	**Shopping Passages**
Meaningful Passage One of the **most** important **exports** of Australia is **wine**. Grapes were originally **planted** in the Hunter **Valley** on the **east** coast, but now there are wine **growing** areas in many **other** parts of the **country**. The warm **climate** and the **rainfall** near the coast make the land **suitable** for the industry. **Winemakers** from Australia have **won** many **prizes** in competitions.	Meaningful Passage One of the **most** important **attractions** in Hong Kong is **shopping**. The citizens **love** to shop in the local **markets** and department stores, but so do the **millions** of tourists who come to **visit** each **year**. The high **quality** goods and low **prices** make the city **ideal** for **shoppers**. Visitors also **discover** that Hong Kong restaurants **are** among the **finest** in the world.
Pseudoword Passage One of the **jilk** important **vezpept** of Australia is **wome**. Grapes were originally **bafjult** in the Hunter **Jerzam** on the **zeat** coast, but now there are wine **flobnis** areas in many **glepo** parts of the **berkald**. The warm **yurpab** and the **torbbret** near the coast make the land **mirabol** for the industry. **Thoncrogur** from Australia have **pum** many **fifoc** in competitions.	Pseudoword Passage One of the **jilk** important **thoncrogur** in Hong Kong is **flobnis**. The citizens **wome** to shop in the local **vezpept** and department stores, but so do the **torbbret** of tourists who come to **fifoc** each **zeat**. The high **mirabol** goods and low **yurpab** make the city **glepo** for **bafjult**. Visitors also **berkald** that Hong Kong restaurants **pum** among the **jerzam** in the world.

Note. There were four reading passages written for this study: one pair of passages about shopping (63 words, one meaningful and one pseudoword passage) and one pair about wine (61 words). The pseudoword passages were derived from each of the meaningful passages by replacing fifteen content words (in bold) with pseudowords.

Figure 2

Number of fixations, regressions, and fixation duration in meaningful passage reading and pseudoword passage reading as a function of reading group.



Note. Error bars indicate one standard error from the mean.

Figure Captions

Figure 1. Passages used in the study. Note. There were four reading passages written for this study: one pair of passages about shopping (63 words, one meaningful and one pseudoword passage) and one pair about wine (61 words). The pseudoword passages were derived from each of the meaningful passages by replacing fifteen content words (in bold) with pseudowords.

Figure 2. Number of fixations, regressions, and fixation duration in meaningful passage reading and pseudoword passage reading as a function of reading group. Note. Error bars indicate one standard error from the mean.