Individuals with dyslexia use a different visual reading strategy to sample text: Comprehensive evidence from eye-tracking

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Abstract

Individuals with dyslexia present with reading-related deficits including slow reading speed, and worse text comprehension and word encoding. Reports of visual symptoms such as atypical eye movements during reading gave rise to a search for these deficits' underlying mechanisms. This study sought to replicate established behavioural deficits in reading and cognitive processing speed while investigating their underlying mechanisms in more detail by developing a comprehensive profile of eye movements specific to reading in adult dyslexia. Using a validated standardized reading assessment, our findings confirm a persistent reading speed deficit among adults with dyslexia. These individuals exhibited slower cognitive processing speed on one type of processing speed task, which correlated with reading speed across all readers. We observed different eye movements in readers with dyslexia across numerous eye movement metrics including the duration of a stop (i.e., fixation), the length of jumps (i.e., saccades), and the number of times a reader's eyes expressed a jump atypical for reading. We conclude that individuals with dyslexia visually sample written information in a laborious and more effortful manner that is fundamentally different from those without dyslexia. Our findings suggest a mix of aberrant cognitive linguistic and oculomotor processes being present in adults with dyslexia.

Introduction

Within today's society, quick and accurate reading skills are essential to participate in societal activities (e.g., education, using social media, communication) and to achieve professional success. Reading is a complex task requiring the eyes, specifically the fovea of the retina, to stop on the written text to successfully encode the sequence of letters that make up each word, and will eventually be assigned meaning (i.e., semantics) during decoding and matching with one's mental lexicon. The stops in eye movements, termed fixations, are an essential part of reading (Rayner, 1985, 1998) and a prerequisite for adequate decoding of a text's content including successful word selection from the mental lexicon (Hawelka et al., 2010). Each fixation is complemented by a brief jump in eye position, termed a saccade, which relocates the fovea to the next part of the text to be processed. Saccades are typically 7-9 characters wide (Rayner, 1985) and take 20 – 30 ms during reading (Rayner & Clifton, 2009). The time available for completing a fixation and its associated linguistic tasks, and planning the next eye movement (a saccade) is approximately 225 – 250 ms per stop (Rayner, 1985; Rayner & Clifton, 2009; Sereno & Rayner, 2003). This duration may be even shorter due to the preview benefit of text appearing outside of the fovea (Snell et al., 2018; Snell & Grainger, 2019). These findings underline the importance of an automatized, rapid interplay of low-level eye movements with higher-level cognitive processing during reading such as lexical, phonological, and semantic processing (Dien, 2009; Hauk et al., 2006; Rayner, 1985).

One group that is well-known to struggle with developing proficient and fast reading skills are individuals with dyslexia. Their struggles express in slow and laboured reading, deficits in reading comprehension, word encoding, word retrieval, and memorizing (Lyon et al., 2003; Shaywitz, 1998). Dyslexia is a language-based neurobiological learning disorder affecting reading, writing and spelling (American Psychiatric Association, 2013), which persists into adulthood (Shaywitz et al., 2003; Swanson & Hsieh, 2009; Vellutino et al., 2004). An estimated 5 to 20% of the population are affected (American Psychiatric Association, 2013; Shaywitz, 1998; Shaywitz et al., 2003; Wagner et al., 2020). Dyslexia's etiology remains the subject of a heated debate with proponents attributing the main underlying cause to deficits in a variety of systems

associated with reading (i.e., phonological awareness, visuo-spatial attention, magnocellular and cerebellar function; Stein, 2001, 2018b; Stein & Walsh, 1997; Stoodley & Stein, 2011), or to a lack of reading experience (Goswami, 2015; Huettig et al., 2018). While deficits in phonological awareness are considered established (Ramus, 2003, 2014; Saksida et al., 2016; Snowling, 1980, 1981), other deficits in low-level sensory processing and visual attention remain under scrutiny (e.g., Blythe et al., 2018).

Most researchers who investigate the reading skills and strategies of individuals with dyslexia have focused on reading speed as a measure of performance (e.g., Bernard et al., 2003; Marinus et al., 2016; O'Brien et al., 2005). These studies report that readers with dyslexia read at a slower rate (i.e., fewer words per minute) compared to readers without dyslexia (Marinus et al., 2016; Spinelli et al., 2002). These reading rates amongst adults affected by dyslexia equate to those of beginning non-dyslexic readers (Trauzettel-Klosinski et al., 2010). However, reading speed rates neither provide insight into the cognitive mechanisms nor the visual sampling strategy by which readers with dyslexia may encode written text differently.

Recent evidence stresses that at least one subtype of dyslexia is affected by differences in visual processing (Joo et al., 2018), which can be detected within eye movement recordings. For example, Benfatto and colleagues (2016) were able to reliably distinguish between individuals at high- and low-risk of dyslexia using a classification algorithm operating on one-minute eye movement recordings. Specifically, the duration of fixations, and the number of fixations, saccades and regressions were found to be the most predictive eye movements for detecting the risk of developing dyslexia later in life. This finding is in line with previous research showing that readers with dyslexia exhibit longer fixation durations (De Luca et al., 1999; Hutzler & Wimmer, 2004; Razuk et al., 2018), an increased number of fixations (Hutzler & Wimmer, 2004), shorter saccades (De Luca et al., 1999; Hutzler & Wimmer, 2004; Rayner, 1983, 1985), fewer skipped words (Bucci et al., 2008; Hawelka et al., 2010; Jainta & Kapoula, 2011). Conversely, the probability of revisiting a previous part of a text (i.e., expressing a regressive saccade also termed regression) has not proven to be reliably different in dyslexia (De Luca et al., 1999; Hawelka et al., 2010).

Many advances in dyslexia eye movement research have been made in recent decades.

Most of our current knowledge about differences in eye movements in dyslexia is provided by researchers investigating either a limited number of eye movement metrics in relation to specific linguistic aspects most often embodied by a target word (e.g., Hawelka et al., 2006; Rayner et al., 2010; Slattery & Yates, 2018), or is limited by the use of a large variety of often controlled but non-standardized linguistic stimuli in several languages with varying orthographic depth ranging from one character up to one or two sentences (e.g., Ashby et al., 2005; Degno et al., 2019; Drieghe et al., 2019; Engelmann et al., 2013). Hence, a comprehensive profile of the eye movements of adults with dyslexia during naturalistic reading of standardized texts of multiple sentences remains surprisingly unknown. The development of a comprehensive profile would allow to uncover and quantify potential inefficiencies in visual sampling of text that have not come to light using the aforementioned focused, local approach. Therefore, we aim to devise a comprehensive eye movement account of adult dyslexia by investigating how eye movement patterns of individuals with dyslexia differ from those without dyslexia on global (text-based) and local (word-based) reading measures during an ecologically valid silent paragraph reading task.

Linguistic parameters such as the difficulty of a text (Rayner & Duffy, 1986; Trauzettel-Klosinski et al., 2010), its syntax (von der Malsburg et al., 2015; von der Malsburg & Vasishth, 2013), or word length and word frequency (Reichle et al., 1998) can impact eye movements, highlighting the importance of using standardized and validated stimuli. To this end, we employed the International Reading Speed Texts (IReST; Trauzettel-Klosinski & Dietz, 2012). The IReST were developed for standardized reading speed assessment, and consist of ten independent texts, each of about 150 words using novel content. The texts have been equated on a global level for their number of words, syntax, sentence complexity and text difficulty, and were designed to be used in repeated measures within-participant paradigms. Each text was accompanied by one brief multiple-choice question that intended to keep readers attentive and read for comprehension. The IReST and their accompanying questions were recently validated in a Canadian sample of adult readers (Morrice et al., 2020).

Based on previous research (e.g., Spinelli et al., 2002; Swanson & Hsieh, 2009), we hypothesize that individuals with dyslexia, compared to an age- and education-matched control

group without dyslexia, will take longer to read each text and show slower cognitive non-linguistic processing speed that is in turn linked to one's reading duration. In terms of eye movements, we hypothesize that readers with dyslexia will express more eye movements (i.e., fixations, saccades, and regressions), longer fixations and shorter saccades. Scanpaths of readers affected by dyslexia are hypothesized to be longer and to differ in their sequence and duration of eye movement events as a result of increases in reading duration.

Figure 1. Experimental paradigm and example of stimuli. a) Pictorial depiction of the sequence of events of one trial. The entire paradigm was participant controlled by pressing the space bar. A drift correction circle (the circle was smaller than depicted) directed the participant's eyes to the starting location of the text. While fixating at it, participants pressed the space bar to get a text to appear that was then read silently once. Immediately after participants finished reading, they were asked to answer a short multiple-choice attention question relating to the content of the preceding text without time pressure. This process was repeated ten times. **b)** Example of one text and its corresponding attention question (panel d) displayed in Times New Roman font. Please note that this text was not presented and just constitutes an example comparable to the texts from the commercial reading assessment (IReST; Trauzettel-Klosinski & Dietz, 2012). The original texts are protected. **c)** Example of the same text and its comprehension question displayed in OpenDyslexic font. **d)** Example of the attention question accompanying the texts shown in panels b and c. Attention questions were always presented in the same font than their preceding text.

Results

In this study, we focused on group-level differences in behaviour and eye movements between adults with and without dyslexia. Behavioural analyses included an investigation of the dependent variables reading duration, attention to the text and non-linguistic cognitive processing speed as a function of the two experimental groups (i.e., Dyslexia and Control). Eye movement analyses examined global (i.e., paragraph/trial-based) and local (i.e., word/interest area-based) metrics of eye movement events during reading.

Behavioral Results

We constructed a generalized linear mixed-effects model (GLMM) for analyzing reading duration as a function of the predictors: *group* (Control and Dyslexia) and *font* (OpenDyslexic and Times New Roman), and their *font-by-group* interaction on a single-trial level. The predictor font was also included as a random effect, which was allowed to vary by participant. In addition, the predictors group and font and their interaction were included as random effects, which were allowed to vary by text. This model was based on 601 experimental trials (i.e., one value for median reading duration per trial) collected from all 67 participants.

This GLMM demonstrates significant predictive power of the main effect of group on median reading duration with individuals with dyslexia taking longer to read each text ($X^2 = 13.431$, $df = 1$, $p < .001$; Fig. 2a, b; see Table 1 for detailed model statistics). This speed difference is underlined by a lower words per minute reading rate among readers with dyslexia ($Median_{Dyslexia} = 178.09$, $Median_{Control} = 248.18$; two-sided independent sample t -test: $t(65) = 20.51$, $p < .001$; $g = 1.67$, 95% $CI_g = [1.486, 1.858]$; Fig. 2a). However, this model yields neither a significant improvement in reading duration with font ($X^2 = 1.41$, $df = 1$, $p = .235$) nor a significant font-by-group interaction ($X^2 = 0.446$, $df = 1$, $p = .504$).

<i>Parameter</i>	<i>Estimate</i>	<i>CI 2.5%</i>	<i>CI 97.5%</i>	<i>SE</i>	<i>t</i>	<i>p</i>
Font	1.097	-0.6593	2.8531	0.896	1.224	0.221
Group	-21.696	-32.3832	-11.0091	5.453	-3.979	< 0.0001
Font * Group	-1.207	-4.7307	2.3167	1.798	-0.671	0.502

Table 1. Generalized linear mixed-effects model fixed effect parameter estimates. Model predicting reading duration. Effects with significant predictive power after post-hoc likelihood-ratio (χ^2) model comparisons in bold.

Secondly, the multiple-choice questions presented immediately after reading each text served as an incentive for participants to read each text for comprehension—hence, constituting an indicator of attention. Both groups demonstrate attention to the texts clearly above chance level (control: $t(31) = 15$, $p < .001$; $BF_{10} = 29.49$; dyslexia: $t(34) = 12.431$, $p < .001$; $BF_{10} = 26.07$; all two-sided paired t -tests; Fig. 2c). However, our data show no significant evidence for a difference between both groups (two-sided independent samples t -test: $t(65) = -0.443$, $p = .33$; $BF_{10} = 1.3$; Fig. 2c). Altogether, this analysis demonstrates that both groups paid attention to the reading material, as their performance is better than chance across all trials.

Thirdly, we examined if there were any non-linguistic cognitive processing speed differences between our two groups using two subcomponents from the Wechsler Adult Intelligence Scale (Coding and Symbol Search; Wechsler, 2008). This analysis was motivated by previous reports of links between reading speed and slower cognitive processing speed in individuals with dyslexia (Breznitz & Misra, 2003). We find that Individuals with dyslexia exhibit slower processing speed on the Coding test (two-sided independent samples t -test: $t(65) = 5.88$, $p < .0001$; $g = 1.422$, 95% $CI_g = [0.895, 1.973]$; Fig. 2d), but not on the Symbol Search test (independent samples t -test: $t(65) = .399$, $p = .69$; $g = -0.1$, 95% $CI_g = [-0.382, 0.577]$; Fig. 2d). Our data show a negative correlation between Coding speed and reading duration across all participants ($r_{65} = -.51$, $p < .0001$, 95% $CI_r = [-0.680, -0.315]$; Fig. 2d) indicating that, in the present study, participants with better coding ability (i.e., faster number related cognitive processing speed) show shorter reading duration. The coding task can encompass working memory performance, since exhibiting higher working memory capacity may constitute a

strategy for achieving a higher score by memorizing symbol-number pairs quickly. Hence, these results may be indicative of working memory deficits in adults with dyslexia—in line with previous reports (Beidas et al., 2013; De Jong, 1998; Fostick & Revah, 2018; Moll et al., 2014; Savage et al., 2007)—and their role in achieving age- and education- appropriate reading speed.

In short, our behavioural results show a sustained level of attention to the stimulus material throughout the study by almost all participants. Though, readers with dyslexia exhibit generally slower reading speed in line with previous reports. One potential explanation of the observed reading speed deficit might be the difference in non-linguistic coding processing speed between groups.

Figure 2. Behavioural results. **a)** Caterpillar plot of median reading speed (words per minute) per participant sorted in ascending order. Blue dots represent participants of the dyslexia group whereas yellow dots represent participants of the control group. **b)** Single-trial reading duration (in seconds) by group. Groups are colour coded as in a. **c)** Attention to the texts as a measure of reading comprehension (i.e., number of correct answers per participant). Colour notation as in panel a. **d)** Cognitive processing speed from the WAIS-IV scale (Wechsler, 2008) by group. Higher scores illustrate faster processing speed. The left-hand side (i.e., yellow/light colour) of each violin plot depicts scores of the dyslexia group; the right-hand side (i.e., blue/dark colour) depicts scores of the control group. Red crosses denote group means, black squares group medians. **e)** Correlation between reading duration and standardized Coding processing speed scores across all participants. Correlation coefficient (r) and p-value shown resulted from a robust bend correlation analysis ($n = 67$). Colours indicate down-weighted data points: red for data in X, green for data in Y and black for data in X and Y. In each dimension, 20% of the data points were down-weighted. This figure is best viewed in colour.

Eye movement profile

This study aims to devise a comprehensive characterisation of the eye movement profile of individuals with dyslexia during natural paragraph reading. This profile comprises eye movement metrics traditionally examined in the field, and other more recent metrics such as line-initial fixation duration, scanpath similarity, and specific saccades atypical for reading. The reading-related metrics covered in this study include global (i.e., trial-/text-based) and local (single-word based) metrics. To establish the significance of a group difference in the frequentist sense, we use unbiased effect sizes (i.e., the 95% confidence interval of Hedges' g not including zero; denoted as g in the text; Hentschke & Stüttgen, 2011; Fig. 5a). A negative effect size indicates a longer duration or larger number exhibited by the dyslexia group and vice versa. High collinearity between some metrics included in our analyses did not allow for the use of a meaningful linear regression approach. In general, where applicable, we report group means alongside group medians to complement this robust measure of central tendency and ensure comparability to previous literature.

Traditionally, average fixation duration and saccade length have been investigated on a global trial level as indices of cognitive processing effort. In an effort to replicate previous findings we computed the same metrics showing that readers with dyslexia stop longer as illustrated by longer mean and median fixation duration ($g_{\text{Mean}} = -1.07$, 95% $CI_g = [-1.244, -0.902]$; $g_{\text{Median}} = -0.96$, 95% $CI_g = [-1.124, -0.786]$; Fig. 3a and 5a), and scan more area of the text as indicated by a longer total scanpath ($g = -0.54$, 95% $CI_g = [-0.706, -0.380]$; Fig. 3b and 5a). While scanning the text, the dyslexia group exhibits shorter average saccade amplitude (i.e., eye movement “jumps” between fixations; $g_{\text{Mean}} = 1.15$, 95% $CI_g = [0.978, 1.323]$; $g_{\text{Median}} = 1.10$, 95% $CI_g = [0.930, 1.273]$; Fig. 3c and 5a), and increased variance (i.e., standard deviation) in these saccade amplitudes ($g = 0.70$, 95% $CI_g = [0.495, 0.823]$). This pattern of results suggests that adults with dyslexia employ a more laborious visual sampling strategy on a global text-level. Longer fixation durations and shorter saccade amplitudes indicate that this group spends more time on information uptake and analysis per stop (i.e., fixation), while also potentially taking up less information per unit of time. A similar pattern of eye movements has previously been associated with individuals who are learning to read (Rayner, 1998), and those who are

considered poor readers (Ashby et al., 2005). The observed longer total scanpaths among readers with dyslexia are a logical consequence of this group's substantial increase in reading duration.

Global metrics, however, do not provide more detailed information on specific elements of the visual sampling strategy in relation to single words such as how many of these words get actively fixated and how often. To address these questions, we complemented the reported global metrics with measures based on the definition of interest areas around single words. We find that individuals with dyslexia spent more time ($g = -1.57$, 95% $CI_g = [-1.75, -1.39]$; Fig. 3d and *First Run Dwell Time* in Fig. 5a), and skip fewer words ($g = 0.40$, 95% $CI_g = [0.235, 0.557]$; Fig. 3e and *Ratio First Run Words Skipped* in Fig. 5a) during first pass reading (i.e., the sum of all first fixations on a word in reading direction excluding any revisits or skipped words). In line, readers with dyslexia fixate on more words on a given trial when all fixations are examined ($g = -1.312$, 95% $CI_g = [-1.488, -1.135]$; *Ratio Visited Words* in Fig. 5a), and stop more frequently per word on average ($g = -1.27$, 95% $CI_g = [-1.445, -1.095]$; *Number Fixations per Word* in Fig. 5a). Further, revisits of earlier parts of a text (i.e., leftward saccades to a preceding word formally called regressions) are a substantial and frequent part of natural reading. We observe that readers with dyslexia express more regressions per text ($g = -0.82$, 95% $CI_g = [-0.989, -0.656]$; Fig. 3f and 5a). However, given the increase in the number of saccades as a result of longer reading durations, the increase in the number of regressions yields no significant difference in the probability of making a regression across an entire text ($g = -0.05$, 95% $CI_g = [-0.213, 0.107]$; Fig. 5a).

Taken together, our results on traditional eye movement metrics corroborate previous findings with readers affected by dyslexia. They demonstrate that readers with dyslexia examine a given text more slowly and in smaller steps, even without accounting for any revisits of previous words. Since efficient reading is characterized by skipping up to 90% of a text during first-pass reading for instance (Hawelka et al., 2010), this pattern strongly suggests that inefficiencies are introduced by processing less content simultaneously as well as slower information uptake and longer cognitive processing times of text. Crucially, these findings are based on data obtained from natural reading of standardized texts consisting of multiple lines.

Figure 3. Group comparison of selected traditional eye movement metrics. Plots display trial-based eye movement metrics that showed significant differences between groups. Each panel depicts the group comparison collapsed across fonts as a raincloud plot for the respective metric. Kernel density plots depict the frequency of occurrence of a value while scatterplots display the underlying values as in one average value per trial. Boxplots indicate the median, upper and lower quartile, and whiskers the 95% CI. Blue (dark) colour represents data of the dyslexia group whereas yellow (bright) colour depicts data of the control group. **a)** Median fixation duration in milliseconds. **b)** Total scan path in degrees of visual angle. **c)**

Median saccade amplitude in degrees of visual angle. **d)** First run dwell time in seconds. That is, the sum of all fixation durations during a first visit to a word if it has not been visited or skipped before. **e)** Ratio of words that were skipped during first pass reading. This excludes all fixations on a word that occurred after a regression to a previous word was completed. **f)** Number of regressions. That is, leftward saccades to preceding words that have already been visited or skipped.

Further contemporary metrics of ocular movements during reading

Recently, additional metrics have been proposed to differentiate between oculomotor deficiencies and cognitive, linguistic factors underlying longer fixation times (Parker et al., 2017). Line-initial fixations are one such metric. They constitute the first fixation on one of the first words of a line that is not followed by a leftwards correction within the same line. Uniquely, line-initial fixations do not allow the reader early access to a word's coarse visual orthographic percept due to absent parafoveal preview. Hence, they have been proposed as an unconfounded indicator of linguistic processing time (Parker et al., 2017; Parker, Nikolova, et al., 2019). By contrasting the median duration of line-initial fixations per trial, we find these to be longer in the dyslexia group on a single-fixation ($g = -0.33$, 95% $CI_g = [-0.276, -0.383]$; $Median_{Dyslexia} = 231$ ms, $Median_{Control} = 202$ ms; Fig. 4a), and single-trial level ($g = -0.81$, 95% $CI_g = [-0.64, -0.972]$; $Median_{Dyslexia} = 256$ ms, $Median_{Control} = 216$ ms; Fig. 4b). Parker and colleagues (2017) reported an effect in the same direction when comparing accurate line-initial fixation durations between children and adults without dyslexia, with children showing longer fixation durations. This finding adds to the evidence indicating that readers with dyslexia take longer to process the visual and linguistic information sampled during a fixation. It further supports the notion that the visual sampling strategy of readers with dyslexia resembles the strategy of beginning readers without dyslexia.

To ensure that we selected line-initial fixations accurately, we compared their duration to the overall median fixation duration of a trial. Previous research shows that fixation duration decreases as readers move their eyes towards the end of a line (Parker et al., 2017; Parker, Slattery, et al., 2019). As expected, the identified line-initial fixations are of longer duration than all fixations considered together ($g_{Dyslexia} = 0.87$, 95% $CI_g = [0.673, 1.071]$; line-initial_{Dyslexia} = 256 ms; All_{Dyslexia} = 224 ms; $g_{Control} = 0.57$, 95% $CI_g = [0.361, 0.768]$; line-

initial_{Control} = 216 ms, All_{Control} = 202 ms). We find this increase in line-initial fixation duration to be larger in the dyslexia group ($g_{\text{Groups}} = -0.37$, 95% CI_g = [-0.526, -0.204]).

Specific divergence from a regular visual sampling strategy

Besides the presented group differences on global and local eye movement metrics, we noticed a clear divergence from a regular left-to-right visual sampling strategy among readers with dyslexia. To quantify these divergences of eye movements that we consider atypical for reading, we examined saccades with angles that would not be expected during the natural reading flow (henceforth directional deviations).

During left-to-right reading of text most saccades will either be expressed in a horizontal rightward direction in line with the expected reading direction or in mostly horizontal leftward direction as revisits of preceding text or in an occasional return-sweep saccade to the beginning of the next line. Yet, not all observed saccades would satisfy any of these typical categories of eye movements, since their expressed angle deviates substantially from the ones expected as part of the usual reading flow. We examined the number of saccades with an angle that considerably deviates from the expected pattern of saccade angles during typical reading behavior (i.e., angles between 35° and 145° upwards and -35° and -145° downwards from the horizontal reading plane). To avoid that falsely programmed return-sweeps were mistaken for directional deviations, we excluded a number of saccades that could be attributed to other eye movements typically involved in reading such as blinks, accurate and inaccurate return-sweeps (see Methods section for details). These corrections resulted in 522 saccades being identified as directional deviations.

Readers with dyslexia express directional deviations more than twice as often per trial on average ($g = -0.48$, 95% CI_g = [0.316, 0.641]; $Mean_{\text{Dyslexia}} = 1.003$, $Mean_{\text{Control}} = 0.441$, $var_{\text{Dyslexia}} = 2.08$, $var_{\text{Control}} = 0.61$; Fig. 4c), which signals a more frequent loss of place at unexpected points during the reading process. Remarkably, in the dyslexia group most of the identified directional deviations were directed straight downwards, whereas this pattern was virtually reversed in readers without dyslexia (Fig. 4c). Our analysis ensured that these differences in directional deviations were not the result of falsely programmed return-sweeps.

Since even a brief scanning of the area of text just below the current fixation seems rather unintuitive from a cognitive perspective, this finding raises the question whether these directional deviations are the result of occasional issues with oculomotor control previously reported in dyslexia (Biscaldi et al., 1998, 2000; Fischer et al., 1993; Fischer & Hartnegg, 2000; Freedman et al., 2017; Stein, 2014, 2018b; Stoodley & Stein, 2011, 2013; Vagge et al., 2015)

The aforementioned differences in eye movements are part of the overall visual sampling strategy of text during reading, termed a scanpath. To investigate whether readers with and without dyslexia differ only on some eye movement metrics or rather use a divergent overall visual sampling strategy, we complemented the previous analyses with a computational similarity analysis of the overall scanpath of each trial. To this end, we quantified the temporal and spatial similarity of the fixations of all scanpaths employing a version of the *Scasim* analysis (von der Malsburg & Vasishth, 2011). The aim of this trial-based analysis was to identify clusters of trials with similar scanpath patterns, while achieving independence of the observed group differences in reading time. To identify whether trials of readers with dyslexia were more similar to those of other readers with dyslexia, we compared the number of trials associated with each group within a given cluster. Similarity scores and clusters were computed separately for each text of the IReST battery and font type, as this coordinate-based analysis is highly sensitive to differences in spacing such as those introduced by text displayed in differently spaced font types (Fig. 1b, c). In this study, trials were equally split between Times New Roman and OpenDyslexic font types. Additionally, all trials were normalized by their reading duration to avoid the introduction of trivial differences between scanpaths of different lengths.

Pairwise scanpath similarity scores showed that trials of participants with dyslexia differed from those of participants without, even though participants read identical texts (Fig. 4d, e, f). Upon normalizing, trial-by-trial similarity scores indicated that dyslexic participants spend a substantial amount of the time (between ~34 and 83%) looking in different places on the identical paragraph and/or for different durations compared to their non-dyslexic counterparts (Fig. 4e). These similarity scores were subsequently transferred to the spatial domain (see Methods for details), where we find the optimal number of group-independent clusters to range between two and five clusters per text-font pair. Trials of each group were

predominantly allocated to separate clusters, and demonstrate a significant difference of association for about 75% of text-font pairs ($p < .05$; see Table 2 in the supplementary material for detailed statistics). Thus, we find that readers with dyslexia sample identical texts using a different sequence of fixations (i.e., fixating different locations on the text and/or for different durations) than non-Dyslexics —even when differences in reading time are accounted for.

Figure 4. Contemporary eye movements typical and atypical for reading. **a)** Duration of all identified line-initial fixations by group. That is, the very first “valid” fixation on the first two words of a line not followed by a leftwards corrective saccade. Boxplots indicate the median, upper and lower quartile, and whiskers the 95% CI. Blue (dark) colour represents data of the dyslexia group whereas yellow (bright) colour depicts data of the control group. **b)** Median line-initial fixation duration per trial by group. Colour scheme and box plot properties as in panel a. **c)** Group comparison of the frequency of directional deviations by angle across all trails depicted as polar histograms. Saccade angle and frequency are depicted in bins of 2.75° width. Only saccade angles between $\pm 35^\circ$ and $\pm 145^\circ$ (displayed as $35/145^\circ$ and $215/325^\circ$) qualified as directional shifts. 0° equals horizontal rightward direction of reading. All other saccades were excluded from this analysis. **d)** Example of two scanpaths after reading the same text (IReST #10) displayed in Times New Roman font. Scanpaths are depicted over time (y-axis) and word-based interest areas (x-axis). Top scanpath depicts trial by a control participant whereas the bottom scanpath of the panel depicts a trial expressed by a reader with dyslexia. **e)** Pairwise, trial-based similarity matrix illustrating differences in

spatial and temporal fixation patterns upon normalization by reading duration. Higher scores (darker colour) denote higher dissimilarity. Pink square frame indicates the Scasim dissimilarity score for the two trials shown in panel d. **f)** Map of clusters of trials in the spatial domain (using the Euclidian distance metric) after multidimensional scaling. Red and black coloured circles denote trials allocated to separate clusters. Grey diamonds indicate the centers of these clusters. Trials framed in yellow and blue represent the spatial equivalent of the same trials whose scanpaths are depicted in panel d. Colours mark groups.

To subsume, our findings demonstrate that substantially slower reading, a behavioural consequence of dyslexia, persist into adulthood—even in individuals attending higher education who were tasked with reading simple, standardized paragraphs of text. We find that readers with dyslexia use a generally more laborious and inefficient visual sampling strategy during natural reading. Replicating previous findings, this strategy is characterised by longer average and line-initial fixation duration, and first run dwell time as well as shorter saccade amplitude and fewer skipped words. Contrarily, the probability of revisiting preceding words was comparable between groups. This pattern of eye movements suggests that prolonged time for cognitive, linguistic processes such as word encoding, lexical access, and/or phonological decoding underlies the behavioural difficulties associated with dyslexia, but not an increased need for resolving semantic or syntactic ambiguities through reanalysis of prior text. Hence, linguistic word analysis appears to be slower but nevertheless successful in adults with dyslexia. The virtually opposite pattern of directional deviations between groups points towards the existence of occasional deficiencies in oculomotor control that result in dyslexic readers losing their place more often. Altogether, these results indicate an interplay of cognitive, linguistic and oculomotor factors in dyslexia.

Figure 5. Summary of effects and visual sampling strategy group profiles. **a)** Effect sizes and their 95% confidence intervals (CIs) of the effect of group on eye movement metrics. Positive effect sizes (i.e., Hedges' g) illustrate a higher number of events, longer duration or distance or a larger ratio for the control group. A negative effect size illustrates the opposite effect. Red dots denote the effect size and black bars the 95% confidence Interval for each effect size. CIs computed using the exact analytical method as implemented in the measures of effect size toolbox (Hentschke & Stüttgen, 2011). Effect sizes were considered significant if the 95% confidence interval did not include zero. **b)** Radar plot depicting overall group differences in the eye movement and reading profile given selected metrics. Plots depict group averages after all trials of each measure were normalized (i.e., z-scored) for comparability. Counter-clockwise direction follows presentation order as in panel a. If two variants of the same metric were present in panel a, only one of them is displayed on the radar plot for simplicity.

Discussion

In this study, we used eye-tracking to devising a comprehensive eye movement profile of the visual sampling strategy of adult readers with dyslexia during naturalistic reading of standardized multi-sentence texts in English (IReST; Trauzettel-Klosinski & Dietz, 2012). Here, combining traditional and contemporary eye movement metrics, we show fundamental differences between readers with and without dyslexia on all but one of the examined metrics. These results, in combination with substantial decreases in reading speed, illustrate a laborious and more effortful reading strategy that persists into adulthood, resembling a pattern observed in beginning (Rayner, 1998) and poorer readers (Ashby et al., 2005).

The idea that eye movements differ between readers with and without dyslexia is not new. Rayner (1983, 1985) was among the first to report different eye movements during reading based on anecdotal case studies with only three dyslexics. His investigations were followed by numerous cross-sectional studies using separate samples of readers with dyslexia, and largely varying stimuli in languages with different orthographic depth (for reviews, see Quercia et al., 2013 and Rayner, 1998). This variety of stimuli, typically consisting of hand-picked single words or short sentences that impose artificial task demands on the reader rather than allowing for an ecologically valid natural reading scenario, constitutes an issue in the field (Schotter & Payne, 2019). The use of standardized and validated multi-sentence texts remains scarce in the literature.

In this work, we were particularly interest in reconciling many previously separate accounts of differential eye movements using the same sample of individuals with dyslexia while also examining specific indicators of oculomotor deficiencies during natural reading. Our results replicate previous findings of differential eye movements in dyslexia such as longer fixation durations, fewer skipped words during first-pass reading and repeated fixations on the same word (Bucci et al., 2008; De Luca et al., 1999, 2002; Hawelka et al., 2010; Hutzler & Wimmer, 2004; Jainta & Kapoula, 2011; Rayner, 1983, 1985; Razuk et al., 2018). Oculomotor control has commonly been investigated using a variety of non-linguistic saccade tracking and

fixation stability tasks (Biscaldi et al., 2000; Fischer et al., 1993; Freedman et al., 2017; Fukushima et al., 2000, 2005; Tiadi et al., 2016). Here, we show that specific saccades atypical for reading can be detected during natural reading. A twofold likelihood of expressing such a saccade, termed directional deviations, indicates signs of occasional oculomotor deficiencies in dyslexia.

To answer the central question about the source of the reading struggles of individuals with dyslexia, all differences across the entire profile needs to be considered. These differences can be explained in the context of established eye movements models that are able to simulate a wide range of reading related patterns including fixation duration, multiple fixations on a word, parafoveal preview benefit, regressions, and spill-over effects—E-Z Reader (Reichle et al., 1998, 2006, 2009, 2013), SWIFT (Engbert et al., 2005), OB1-Reader (Snell et al., 2018). While these models were devised to explain the reading process of typical readers, they can also provide insight into the processes of beginning (Mancheva et al., 2015; Reichle et al., 2013) and dyslexic readers (Hawelka et al., 2010; Reichle et al., 2009). Particularly, the extensive research on the E-Z Reader model, and its prior application to data obtained from dyslexic readers, makes it an interesting model for our study. It is a serial processing model which posits that processing of the fixated word occurs in four separate stages, beginning as soon as the preceding word (N) is fixated on and attention is allocated. First, information about the upcoming word (N+1) is extracted from the parafovea during pre-attentive visual processing. Second, a *familiarity check* is performed upon fixation. The length of this familiarity check is depended on the word's frequency and word length. Once a word is processed for lexical familiarity, it signals the initiation of an eye movement. Third, *completion of full lexical access* leads to a shift in attention to the next word (N+1) in the form of a saccade. Fourth, an integration of the identified word in the syntactic context is carried out simultaneously and may trigger a regressive saccade if a syntactic or semantic conflict is detected (Reichle et al., 1998, 2006, 2009).

In the case of individuals with dyslexia who present with longer fixation durations, as seen in the current study, this model posits that these individuals experience slower lexical access, associated with increased lexical processing demands. Where skilled readers require less time to perform the usually fast familiarity check (i.e., finding a match for the letter string making up a word), individuals with dyslexia do not seem to be able to carry out this process equally fast. The dyslexia group also expressed shorter saccades and skipped fewer words during first-pass reading—in line with previous findings (Hawelka et al., 2010; Rayner, 1983, 1985). These findings, in combination with a higher frequency of fixating on the same word repeatedly, corroborate the notion of needing to process each word or even its sub-components individually, and for longer, when reading for comprehension. Prolonged line-initial fixations of individuals with dyslexia in our study provide more evidence for delays in lexical access (stage two and three). These first fixations on a line do not benefit from any parafoveal preview benefit (first stage) resulting in the sole reliance of information sampled during this fixation for word identification purposes.

While a deficit in lexical processing can explain longer fixation durations for individuals with dyslexia, a deficit in parafoveal processing could likewise explain increased fixation durations, shorter saccade amplitudes and fewer skipped words. The preview benefit takes advantage of orthographic information from parafoveal vision such as word length and word familiarity. It is linked with a reader's perceptual span, which is defined as the number of distinct characters from which useful information can be acquired in parallel across the fovea and parafovea (McConkie & Rayner, 1975; Rayner et al., 2010; Rayner & McConkie, 1976). Should individuals with dyslexia present with such a deficit, removing or having a reduction in this preview benefit could also result in the need for longer processing/fixation durations when the next word is being fixated on simply due to reduced pre-processing of its orthographic percept (Kliegl et al., 2006). Such a smaller perceptual span has previously been associated with reading speed (Ashby et al., 2012; Häikiö et al., 2009), and reported in dyslexia (Rayner, 1998; Rayner et al., 1989). This deficit can occur independently of a phonological deficit (Bosse et al., 2007), however, previous evidence is inconclusive (Phillips & Edelman, 2008; Silva et al., 2016).

In this study, line-initial fixation duration can serve as an indicator of parafoveal processing when compared to all other fixation durations across a sentence, as fixation durations usually decrease towards the end of a line due to absent parafoveal preview for line-initial fixations (Parker et al., 2017; Parker, Nikolova, et al., 2019; Parker, Slattery, et al., 2019). These line-initial fixations were longer for all readers compared to the median fixation duration across a trial. This difference was larger for readers with dyslexia which suggests that these readers need even more processing time when no preview benefit is available. This result demonstrates that a reduction in the perceptual span is unlikely the explanation for the general increases in fixation duration as seen in this study's sample with dyslexia, as they do not appear to be disadvantaged when the preview benefit for words to the right of a fixation is available.

Another conceivable reason for explaining dyslexics' reading struggles is that readers with dyslexia encounter increased semantic and syntactic processing difficulties. These difficulties would lead to revisits of previous words, as illustrated by the frequently observed increase in the number of regressive saccades (Rayner, 1983, 1985; Razuk et al., 2018; Trauzettel-Klosinski et al., 2010; Vagge et al., 2015). In the E-Z Reader model, regressions are conceptualized as difficulty with integrating the identified word within the greater sentence context—occurring during a fourth post-lexical integration stage. In line with previous literature, we observed a greater number of regressions per trial in individuals with dyslexia. Vagge and colleagues (2015), similar to our work, reported this result for a study that also found slower reading speed. However, the higher number of regressions in both studies may simply be a result of longer reading durations, since we did not find a difference in the probability of making a regressive saccade in relation to the overall number of saccades of a trial. This absent regression probability difference replicated an earlier report with dyslexic adults (Hawelka et al., 2010). With the E-Z Reader model in mind, our findings speak against a deficit in the post-lexical integration stage of reading leading to the observed reading struggles in this study (Reichle et al., 2009).

Although the traditional eye movement metrics reported in this work suggest that prolonged lexical processing time underlies the slower reading speed and visual profile in dyslexia, the role of oculomotor deficiencies is far from being established in the literature (Blythe et al., 2018; Quercia et al., 2013; Stein, 2018a, 2018b). Their role has been at the center of the on-going dyslexia debate. To investigate potential oculomotor deficiencies during natural reading, as opposed to saccadic tracking and fixation stability tasks, we examined saccades that are unexpected or atypical in the reading flow of a skilled reader. We should consider horizontal rightward, leftward and diagonal return-sweep saccades reading related. One may even include saccades pointing upwards in this list, since they might constitute a sudden double-checking of previously read content. However, readers with dyslexia jumped away from some fixations in directions atypical for reading such as straight downwards more often than their counterparts. We found the directional pattern of these atypical eye movements to be virtually reversed between groups. This indicates that common eye movements such as blinks were not falsely identified as directional deviations in either group as they should have resulted in a similar pattern of directional deviations (see Methods for details). The nature and frequency (i.e., ~1 per trial) in the dyslexia group suggest that these directional deviations may be a residual of oculomotor deficiencies that persist, but only occur occasionally, in adults with dyslexia attending higher education. Thus, differences in oculomotor control appear unlikely to be the origin of their reading struggles—at least in the present sample of individuals with dyslexia.

One conceivable concern of the current study's design is that the observed eye movement profile could be simply a result of texts that were too difficult for readers with dyslexia, since increases in text difficulty were reported to lead to more eye movements in dyslexic children (Trauzettel-Klosinski et al., 2010), and a pattern similar to the one observed in this study in readers with (Rayner, 1985) and without dyslexia (Rayner & Clifton, 2009). However, given that the IReST are designed at a grade six reading level and all of the participants of the present sample had previously attended or were attending higher education

at the time of participation, unsuitable text difficulty is very unlikely to be the reason for the observed differences.

Second, we aimed to provide a comprehensive descriptive profile that can be paired with predictions from established models of eye movement control. However, this profile itself may not be used to confirm causality of the deficits underlying the general struggles of individuals with dyslexia. This profile may serve as a basis for more targeted investigations in the future probing the specific nature of the presumed deficit in lexical access and its direct causal link to the cognitive mechanisms of the reading difficulties. In this respect, the extensive debate on the etiology of dyslexia is in dire need of more longitudinal investigations starting in kindergarteners to increase the likelihood of being able to establish such causal links reliably through observing the pre-reading state and its change over time.

In summary, the presented eye movement profile of adults with dyslexia demonstrates a laborious and effortful visual sampling strategy that persists into adulthood. Specifically, the combination of prolonged fixation duration, shorter saccade amplitude and fewer skipped words suggests deficits in the linguistic processing components of reading such as fast and efficient access to the mental lexicon. Longer line-initial fixation durations were particularly indicative of prolonged lexical analysis. On the contrary, we did not find convincing evidence for a perceptual span deficit or increased difficulties in the semantic or syntactic post-lexical processing stage of reading. An increased number of eye movements atypical for reading shows that the eyes of readers with dyslexia occasionally move to seemingly random places on a page. Hence, occasional oculomotor deficiencies should not be categorically dismissed in dyslexia.

Methods

Participants

We tested 73 participants: 35 adults with an official diagnosis of dyslexia, and 38 without symptoms of dyslexia. Six individuals from the control group were excluded from analysis due to large inaccuracies during the calibration procedure (best eye with average error > 0.5° and max error > 1.3°). Hence, the final data analysis was conducted on 67 participants: 35 with dyslexia (female = 23, $Mean_{age} = 23.70$, $SD_{age} = 2.58$) and 32 without (female = 32, $Mean_{age} = 22.63$, $SD_{age} = 3.34$).

To delineate between control participants who experience dyslexia symptoms but have not been given an official diagnosis, and to get a measure of severity of dyslexia symptoms at the time of participation, all participants completed the Adult Dyslexia Checklist (Smythe & Everatt, 2001). This checklist assesses aspects of literacy, language, word finding, and organisation skills on a scale of 1–4 (i.e., *rarely / occasionally / often / most of the time*). As specified by the original authors, a score of 45 or more points indicates mild to severe dyslexia symptoms (Smythe & Everatt, 2001). We used a score of ≤ 40 points as a conservative cut-off for our control group, with all formally diagnosed dyslexics allocated to the dyslexia group.

Participants were matched on age and level of education. They were either current or former college or university students at anglophone institutions in Canada. Since participants were recruited in Montréal, a bilingual English-French city, our sample comprises both bilingual and monolingual English speakers (bilingual_{Dyslexia} = 18, monolingual_{Dyslexia} = 17; bilingual_{Control} = 9, monolingual_{Control} = 23). To avoid introducing a language effect, we compared bilingual to monolingual participants and found no evidence for a difference in reading duration in the dyslexia group ($t(33) = 1.829$, $p = 0.765$; $g = 0.6$, 95% $CI_{Dyslexia} = [-0.064, 1.264]$; $BF_{10} = 1.16$) nor the control group ($t(30) = -0.5$, $p = .6212$; $g = -0.19$, 95% $CI_{Control} = [-0.94, 0.56]$; $BF_{10} = 0.4$). We also did not observe a language effect regarding attention to the text in the dyslexia group ($t(33) = 1.44$, $p = .1605$; $g = 0.396$, 95% $CI_{Dyslexia} = [-0.268, 1.072]$; $BF_{10} = 0.72$), and insufficient evidence in the control group ($t(30) = -2.399$, $p = .02$; $g = -0.86$, 95% $CI_{Control} = [-1.634, -.007]$; $BF_{10} = 0.77$). Based on these findings, groups were collapsed across language for all analyses.

Participants could choose between receiving \$10 or course credit as compensation. This study obtained approval by the Concordia University Human Ethics Research Committee (UHREC Certificate: 30003975).

Stimuli

In this study, we used the International Reading Speed Texts as stimuli (Trauzettel-Klosinski & Dietz, 2012). These are 10 texts that have been equated based on their number of words, syntax, sentence complexity and text difficulty, and are designed for use as repeated measures within participants. Additional to their original validation in a UK sample, the IReST texts have been validated in an adult Canadian sample (Morrice et al., 2020). As is common practice in reading studies, each text was accompanied by one short multiple-choice question with three options of which one was correct (for examples, see Figures 1b, c, d). This attention question was presented immediately after reading a text. These questions have been used in other reading studies (Morrice et al., 2017, 2020). Five texts and their accompanying multiple-choice questions were displayed in the specific dyslexia font OpenDyslexic (opendyslexic.org), with the other five texts and questions being displayed in Times New Roman font. Sentence start and end words were identical between the font versions resulting in identical launch and landing interest area sites across font conditions. To equate for differences in physical text size, we varied the nominal font sizes using 20-point size for Times New Roman and 18-point size for OpenDyslexic trials. Text height was comparable. Every text and its respective multiple-choice question were presented in the same font. Due to copywrite restrictions by virtue of the text being a commercial reading assessment, we are unable to provide the reader with the 10 texts.

The Wechsler Adult Scale of Intelligence's Symbol Search and Coding subtests were administered to assess processing speed abilities of all participants (WAIS-IV; Wechsler, 2008). Importantly, both subtests use non-linguistic measures. In the Symbol Search task, participants were shown two target symbols and were instructed to identify both of the target symbols within the adjacent search group. This task involves no working memory as the symbols change for each trial (i.e., by horizontal search group of five symbols). Contrarily, the coding tasks may involve aspects of working memory. Participants were shown numbers 1–9 and their unique

corresponding symbol. Here, the task was to draw the corresponding symbol associated with each as number below the presented numbers. The WAIS has an internal consistency score of 0.87–0.98 on processing speed index tasks. The interscorer agreement ranges from 0.98–0.99, and intraclass correlation from 0.91–0.97 (Canivez, 2010). Correlations between scores on tests that measure similar constructs were in the 0.8 range on criterion-related validity measures (Schraw, 2010).

Procedure

The Adult Dyslexia Checklist (Smythe & Everatt, 2001) was first completed, after which the experimenter administered the WAIS symbol search and coding tasks (Wechsler, 2008). Subsequently, participants were calibrated to the eye tracker (EyeLink 1000) by looking at a series of 9 equally spaced dots on grey background across the screen (using the SR EyeLink's inbuilt 9-point calibration procedure with targets in the default locations). A validation procedure using the same 9 points in a randomised order confirmed the accuracy of the eye tracker's calibration measurements, with participants' better eye needed an accuracy of < 0.5 degrees on average, with no point exceeding 1.3 degrees of maximum error. Upon successful calibration, participants were instructed on screen and verbally to read the 10 texts once thoroughly in silence. They may go back and reread words or entire sentences but once they had reached the end of the text and attempted to start from the beginning they were immediately stopped by the experimenter. Each text was presented separately (five in OpenDyslexic, five in TNR font). We displayed texts in the upper half of the screen with 83.57 characters per line on average and left alignment (Fig. 1a). Once a participant finished reading, they pressed the spacebar, subsequently a multiple-choice question concerning the previously read text appeared. We randomised the presentation order of these 10 texts within-subjects (using the *randperm* function in MATLAB). An additional text with similar linguistic properties, comparable to the text in Fig. 1b and c, and a multiple-choice question was presented as a practice trial in Arial regular font. After completing the reading portion, participants filled out a questionnaire concerning their experience reading the 10 texts as well as demographic

information such as age, mother tongue and education. In total, the experiment lasted between 30 and 45 minutes.

Apparatus

Stimuli were presented and data collected using an iMac (2011 27" i7, 16GB RAM) with an external monitor (View Sonic G225fb 21" CRT, 1024 x 768 pixel resolution, 100 Hz refresh rate). A chin rest was used to stabilize head position at a distance of 70 cm from the screen. Eye position was acquired non-invasively using a video-based eye movement monitor (EyeLink 1000 running host software version 4.56, SR Research, Ottawa, Ontario).

Eye Tracking Analysis

Blinks, fixations, and saccades were recorded at a sample rate of 1000 Hz and stored for offline analysis. During offline analysis, we used inbuilt algorithms in DataViewer (version 3.1.97, SR Research, 2017, Ottawa, Ontario) for pre-processing of the aforementioned event types, forming reading-related interest area analysis and aggregating measures on a trial-by-trial basis. To avoid contaminating our eye movements analysis with reading unrelated events at the beginning and end of each trial, we defined an interest period in DataViewer that excluded the first and last 300 ms of each trial. In the case of a fixation spanning any of these two cut-off time points, the spanned fixation duration was trimmed. Additionally, we set the threshold of the minimum fixation duration to 50 ms, the fixation merging amplitude to 1°, the minimum saccade amplitude to 0.5°. We did not merge fixations separated by a blink, but instead removed fixations immediately before and after a blink and excluded fixations beyond display bounds (i.e., the entire screen). All samples that were identified for exclusion on the grounds of any of the aforementioned criteria were excluded from all further analyses. Choosing these analysis parameters helps to remove outliers caused by random eye movements unrelated to reading. In general, we only analysed data of one eye per participant.

Furthermore, each word was associated with an interest area including five pixels of padding around all sides of a word. We filled gaps between interest areas and chose a background RGB threshold of less than 350. All fixations were drift corrected by the drift value

obtained at the start of each trial. Nevertheless, on trials where all fixations exhibited an obvious vertical offset across all lines of a text resulting in fixations lying on interest area boundaries, as examined by visual inspection, we manually adjusted all fixations of a given trial vertically (13.9% of all analysed trials). Importantly, we neither adjusted fixations horizontally nor moved single fixations separately.

Results of the offline analysis with DataViewer (version 3.1.97, SR Research, 2017, Ottawa, Ontario) were exported to MATLAB (version 2020a, The MathWorks Inc., 2020, Natick, Massachusetts). There, using custom scripts, we calculated all measures split by experimental conditions (i.e., group and font). We excluded all trials presenting text number five in either font (10% of all trials). To quantify and compare the effect of group (i.e., dyslexia vs control) in detail, we computed unbiased signed between-group effect sizes (g) and their respective 95% confidence intervals separately for each eye movement metric (using the *mes* function of the Measures of Effect Size Toolbox by Hentschke and Stüttgen (2011) and its *exact analytical* method for determining confidence intervals). Following frequentist logic, a significant effect of group was presumed when the 95% confidence interval of an effect size did not include zero. In our design, positive effect sizes represent a higher number or ratio of the respective eye-tracking metric for the control group compared to the dyslexia group and vice versa (Fig. 5a). As well, we estimated the probability density function corresponding to selected eye-tracking metrics whose between-group font comparison yielded a significant effect size employing kernel density estimation in MATLAB (using the *raincloud_plot* function by Allen et al., 2019). In doing so, we created a probability density heat map for all selected eye movement metrics.

In addition to traditional reading eye movement measure/metrics, we also examined line-initial fixations. These fixations have been proposed to be able to dissociate binocular coordination from linguistic analysis of text/words (Parker, Nikolova, et al., 2019). We identified the first fixation on any of the first three words of a line that was not followed by an undersweep corrective saccade to the left of this fixation as accurate line-initial fixation. Group differences within these fixations were then quantified using Hedges' g .

Furthermore, we compared the two experimental groups on saccades that are unlikely or unexpected during typical reading behaviour/flow. Such saccades were the ones showing

radical angular shifts with an angle between $\pm 35^\circ$ and $\pm 145^\circ$, which we termed directional deviations. These saccades could not be classified as (in)accurate forward, regression, undersweep, return-sweep or blink saccades. In the computation of these directional deviations, we excluded angles of rightward and leftward saccades typically and frequently involved in reading. All saccades with a blink before, during or after the directional deviation saccade in question, as identified by DataViewer's built-in algorithm (version 4.1.1, SR Research, 2019, Ottawa, Ontario), did not qualify either. Further, saccades representing correctly or programmed return-sweeps to the beginning of the next line were excluded (Parker, Nikolova, et al., 2019). Return-sweeps were identified by finding potential directional deviations that were launched within 3 words of the final word of a line and landed within the first three words (i.e., interest areas) of the next line. Last but not least, incorrectly programmed return-sweeps (so-called "undersweeps"; Parker et al., 2017) were excluded from this analysis as well, since they are normally not assumed to be involved in on-going linguistic processing (Parker, Slattery, et al., 2019). These only had to be launched from any of the final four words of a line.

As an overall measure of scanpath similarity, we computed the *Scasim* metric proposed by von der Malsburg and Vasishth (2011). This trial-based metric compares the location (x-, y-coordinates) and duration of all fixations that make up a scanpath and can be computed in RStudio using the *scasim* function provided by the first author's GitHub repository (www.github.com/tmalsburg/scanpath/). The resulting score represents a value of dissimilarity. We normalized all scores by their respective reading duration to avoid confounds due to extreme differences in reading duration. Scasim scores are computed on a pairwise trial-by-trial basis. Since this measure uses the x-,y-coordinates of a fixation's location, we computed Scasim scores per IReST and font a text was displayed in. This was necessary as differences in font led to words of the same text being displayed in slightly different locations. Trials were analysed across groups to begin with. However, to quantify scanpath similarity between readers with and without dyslexia, spatial maps of scanpaths were fit on similarity scores using Euclidean distances (*dist* function) and non-metric multidimensional scaling (*isoMDS* function from the *MASS* package by Venables and Ripley, 2002). Subsequently, we used the optimal number of clusters, a result of a calculation of Gaussian mixture models paired with the Bayesian

Information Criterion (Schwarz, 1978; *mclustBIC* function of the *mclust* package by Scrucca et al., 2016), as the number of clusters in a k-means clustering procedure (*kmeans* function). Since the determined clusters were still comprised of group-independent trials, we employed chi-square and Fisher exact tests of association analysing whether trials in each cluster belonged to the same or a different experimental group. The entire Scasim analysis was conducted in RStudio (RStudio Team, 2020).

Statistical Analysis

To investigate potential differences in reading duration as a function of dyslexia (i.e., group factor) and font between individuals with and without dyslexia, we used a generalized linear mixed-effects model (GLMM). Eye movement data was primarily analysed using unbiased effect sizes (i.e., Hedges' g ; denoted as g in the text) and their exact analytical 95% confidence interval (Hentschke & Stüttgen, 2011).

We performed the GLMM analysis employing the *lme4* package (Bates et al., 2015) and the *bobyqa* optimizer in RStudio (RStudio Team, 2020). *Reading duration* was specified as a continuous dependent variable, and examined as a *gamma* model in the family argument of the *glmer* function as a function of the two categorical predictors: *group* (i.e., dyslexia and control), and *font* (i.e., OpenDyslexic and Times New Roman), and their interaction on a single-trial level. All GLMMs included the maximal random effects structure justified by the experimental design (Barr et al., 2013). They included all main effects and interactions of our two predictors, group and font, as well as by-subject and by-item random intercepts and random slopes for all relevant main effects. We excluded random correlations this model. The 95% confidence intervals were calculated for all β estimates (using the *broom* package and *Wald* method in RStudio). We accounted for small imbalances in trial numbers of the predictors' levels by entering all predictors in mean-centred form (deviation coding). All entered predictors were checked for collinearity (using the *cor* function and model output in RStudio). Lastly, we used post-hoc likelihood-ratio (X^2) model comparisons to quantify the predictive power and exact significance level of all initially significant or trending effects (i.e., $p < .1$) revealed by the GLMM.

To examine potential effects of non-linguistic cognitive processing speed on reading duration (i.e., the WAIS subscale scores), particularly in light of a difference in reading duration

between experimental groups, we correlated the standardised scores for the processing speed measure that showed a significant group difference—the WAIS Coding test—with reading duration across participants. This and all other correlations were computed employing robust bend correlations (Pernet et al., 2013) and the default of 20% bending in each direction.

To investigate each groups' attention to the reading material separately, we compared their results on our attention questions against chance (i.e., 50% = 4.5 correct answers) using two separate one-sample *t*-tests as well as a Bayes Factor analysis. The latter analysis allowed us to quantify the strength of the evidence in support of the null hypothesis of no difference between groups. Due to a lack of previous research using Bayes Factors in this area, we used an uninformed prior for the Bayes analysis with a Cauchy width of 0.7. We also contrasted the two experimental groups against each other by means of a one-tailed independent samples *t*-test, under the assumption that participants without dyslexia would perform better than those with dyslexia. All *t*-tests were Bonferroni-corrected by the number of *t*-tests evaluating this dependent variable (i.e., $n = 3$).

All trials presenting text number five (had to be excluded from all analyses because this text was displayed in a dissimilar font size on trials written in Times New Roman font (5% of all trials). To avoid any bias, all trials presenting text number five were excluded from all data analyses (10% of all trials).

Acknowledgements

This work was supported by a Concordia University Seed fund and a Horizon Postdoctoral Fellowship awarded to LF.

Author contributions

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Data Availability

Data is available from the authors upon request and will also be uploaded to the project's Open Science Framework repository upon acceptance of the manuscript.

Code Availability

Code will be uploaded to the project's Open Science Framework repository upon acceptance of the manuscript.

Competing interests

The authors declare no competing interests.

Supplementary Material

<i>Text #</i>	<i>Font</i>	<i>Design</i>	<i>Test</i>	χ^2	<i>df</i>	<i>Cramer's V</i>	<i>Alt. Hypothesis</i>	<i>p</i>
1	TNR	4 x 2	Fisher				2-sided	< .0001
2	TNR	2 x 2	chi-square	12.725	1	0.631		< .001
3	TNR	2 x 2	chi-square	10.72	1	0.598		0.001
4	TNR	3 x 2	Fisher				2-sided	0.0548
6	TNR	2 x 2		6.0942	1	0.452		0.008
7	TNR	2 x 2	Fisher				odds ratio $\neq$ 0	0.0184
8	TNR	2 x 2	Fisher				odds ratio $\neq$ 0	0.0184
9	TNR	5 x 2	Fisher				2-sided	0.0137
10	TNR	2 x 2	chi-square	8.601	1	0.503		0.003
1	OD	2 x 2	chi-square	11.765	1	0.588		< .001
2	OD	2 x 2	chi-square	1.821	1	0.231		0.177
3	OD	3 x 2	Fisher				2-sided	< .0001
4	OD	2 x 2	Fisher				odds ratio $\neq$ 0	0.1026
6	OD	3 x 2	Fisher				2-sided	0.0016
7	OD	2 x 2	chi-square	4.136	1	0.354		0.042
8	OD	3 x 2	chi-square	17.376	2	0.726		< .001
9	OD	2 x 2	chi-square	0	1	0		1
10	OD	2 x 2	chi-square	2.346	1	0.271		0.126

Table 2. Results of tests of association. Results were either obtained using a chi-square test of association between a cluster of trials with similar scanpaths and trial count by group in each cluster. Where not applicable due to zero counts of a group for a given cluster the Fisher exact test was computed as an alternative but only returns a P value. The “Alt. Hypothesis” column refers to the alternative hypothesis used by the Fisher exact test. The Yates’ continuity correction was applied to the Cramer’s V effects size when a chi-square test was computed. All statistical tests were computed separately for each text-font pair of the IReST. Tests with significant results are highlighted in bold.

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