An experimental eye-tracking study of text adaptation for readers with dyslexia: effects of visual support and word frequency

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Abstract

Easy-to-read guidelines recommend visual support and lexical simplification to facilitate text processing, but few empirical studies confirm a positive effect from these recommendations in individuals with dyslexia. This study examined the influence of the visual support and lexical simplification on sentence processing through eye movements at both the text- and word-level, and the differences between readers with and without dyslexia. Furthermore, we explored the influence of reading experience and vocabulary, as control variables. We tested 20 young adults with dyslexia and 20 chronological age-matched controls. Participants read 60 sentences in total. Half the sentences contained an image and the other half did not, and half contained a low-frequency word and half a high-frequency word. Results showed that visual support and lexical simplification facilitated sentence processing, potentially by jointly facilitating lexical semantic access. We also found that participants with lower print exposure and lower vocabulary benefited more from word-level lexical simplification. We conclude that both adaptations could benefit readers with low print exposure and smaller vocabularies, and therefore, to many dyslexic readers who show these characteristics.

Keywords: dyslexia, eye movements, visual support, lexical simplification, sentence processing

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There are guidelines and recommendations for simplifying written materials aimed at improving text readability for people with reading difficulties (Freyhoff et al., 1998; Tronbacke, 1997). The aim of these guidelines is to create or adapt written material to an *easy-to-read* style for people who struggle to access information from text for different reasons. The guidelines include adaptations of format (of letters, lines, paragraphs, spelling, or space distribution), lexical adaptations (vocabulary, lexical units), morphosyntactic changes (types of syntax, connectors, ellipsis, anaphoric recurrence, verbal forms), specific organization and structure of the text, provision of graphic support (drawings, illustrations, images), and changes in pagination. Despite the relatively large number of guidelines, there are few studies aimed at evaluating experimentally whether these recommendations actually facilitate reading, especially in the case of readers with dyslexia, and whether the recommendations are specifically applicable to this learning disability. Changes in font type, font sizes, character spacing, colour of the text, or colour of the background, have been recommended and evaluated in persons with dyslexia, but less attention has surprisingly been paid to the adaptation and access to text content itself (Rello & Baeza-Yates, 2013; Rello & Baeza-Yates, 2017; Schneps et al., 2013).

Visual support in easy-to-read texts

Our study focuses on the impact of a much recommended adaptation in easy-to-read guidelines: the use of visual representations to facilitate text comprehension (i.e. graphical support). Images, illustrations, or symbols can accompany text or written information, so that when readers encounter a part of the text they do not understand or an unknown word, the visual representation can be used to bootstrap the understanding of the sentence/text. According to the *multimedia principle* of the cognitive theory of multi-media learning (Mayer, 2009), people learn more from words and pictures combined than from words alone. This is because using images and words together effectively facilitates generative processing, that is, reducing the effort or cognitive load required of students to understand the material, and thus, promoting/enhancing learning.

However, there are several studies that have empirically evaluated the facilitation of understanding in easy and difficult texts with the use of images or symbols, but results have been mixed and do not specifically address readers with dyslexia. For example, Yaneva (2016) used three educational texts in two versions: the original texts, which had no accompanying images and the original texts with images. She wanted to examine whether the texts-with-images facilitated comprehension in people with autism. Yaneva found that the inclusion of images to accompany complex words had no effect on comprehension for adult participants with autism or for neurotypical adults. Dye et al. (2007) assessed the ability to give consent by participants with intellectual disabilities with several different versions of a questionnaire: Control (information followed by a questionnaire), Section (information presented in sections and asking questions after each one), and Photography (information accompanied by six photographs, followed by a questionnaire). They found no significant differences in the ability to consent between experimental conditions. Poncelas and Murphy (2007) examined whether a symbol-based manifesto increased understanding in people with intellectual disabilities. They created two versions of a simplified manifesto: one text-based and the other symbol-based (with text). Both versions produced relatively low levels of understanding, without significant differences between them. However, Jones et al. (2007) evaluated the comprehension of adults with learning disabilities on texts with symbols. They used four passages of texts, of which half had symbols, and 12 comprehension questions associated with the symbolized text and 12 related to “plain” text. The participants' comprehension scores were significantly higher for the symbolized passages than for the non-symbolized ones. Thus, the literature on image support on comprehension is mixed, and as mentioned previously, no work has assessed image support in dyslexia.

Lexical simplification

Lexical simplification is another recommendation included in easy-to-read guidelines. It consists in the substitution of low-frequency words, which are not common and perhaps unknown to the reader, with high-frequency words, which are known and used more often in oral and written language. The effect of word frequency on reading behaviour has been amply demonstrated in eye-tracking studies: there are fewer and shorter fixations on frequent words compared to infrequent words (Inhoff & Rayner, 1986; Just & Carpenter, 1980; Kliegl et al., 1982; Rayner, 1977; Rayner & Raney, 1996). In general, data supports the idea that, higher word frequency is associated with facilitated lexical access, that is, more frequent words are read faster (Ashby et al., 2005; Hyönä & Olson, 1995; Inhoff & Rayner, 1986; Rayner & Duffy, 1986; Rayner & Fischer, 1996; Rayner et al., 1996).

Reading time and accuracy studies, which directly examined the effects of word frequency, in adult dyslexic readers found that low-frequency words are indeed more difficult for dyslexics to process (Suárez-Coalla & Cuetos, 2015; Rüsseler et al., 2003). Eye tracking studies also support these findings. Hyönä and Olson (1995) examined fixations of young adults with and without dyslexia, while they read aloud two texts. They found significantly longer gaze durations and re-inspection times on low-frequency and long words, compared to high-frequency and short words. Rello et al. (2013) compared reading of texts in which words were substituted by shorter/longer and more/less frequent synonyms in individuals with and without dyslexia. They found non-dyslexic participants read significantly faster and had shorter fixation durations than those with dyslexia. However, dyslexics read significantly faster and had significantly shorter fixation durations with high-frequency and shorter words, which also increased their text comprehension. Jones et al. (2007) evaluated regularity effects between adults with developmental dyslexia and control readers. They used regular-, irregular-consistent and irregular-inconsistent low- and high-frequency words (regular words are words with transparent grapheme-to-phoneme correspondence). They found that dyslexic readers took longer and returned more often to target words. More importantly, for both groups they observed that frequent words elicited significantly shorter initial fixations than infrequent words. This indicated that dyslexic readers process intrinsic orthographic or phonological word properties more easily when words are familiar, thus providing support for the recommendation of lexical simplification in dyslexia.

The current study

In the present study, we attempted to empirically validate the impact of easy-to-read guidelines of visual support and lexical simplification, and their possible interaction, in readers with dyslexia. As described above, lexical access, especially for low-frequency words, can be an issue which slows down reading and hinders comprehension in dyslexic readers. Pictorial support has been recommended generally, but it is not clear whether it is a useful adaptation for dyslexic readers. More interestingly, we explored whether a visual scenario accompanying a sentence does not only provide support for general comprehension of a sentence, but also a facilitating context which impacts positively on the lexical processing of a target word within the sentence. Many studies have evaluated the effect of word frequency on reading (Inhoff & Rayner, 1986; Just & Carpenter, 1980; Rayner & Duffy, 1986; Staub, White, Drieghe, Hollway, & Rayner, 2010), but none have observed whether the support of a visual representation of the sentence can facilitate the processing of high- and low-frequency words.

This study relied on the use of eye-tracking technology and measures. Over many years of eye-tracking reading research some standard word-based measures have emerged (Inhoff & Radach, 1998; Liversedge & Findlay, 2000; Rayner, 1998; Rayner et al., 1989). One of them is *reading time*, which is the sum of the duration of all fixations on the word, including regressions back to the word. It is also known as total dwell time, cumulative dwell time, glance duration, gaze, or total fixation time (Holmqvist et al., 2011). *Gaze duration* is the sum of the duration of all fixations on a word, excluding any fixations after the eyes have left the word. In the reading research communities, there are other terms for this measure like first-pass dwell time, first-pass gaze duration, and first-pass fixation time (Holmqvist et al., 2011). *Regressions out* are backward movements to previously read parts of the text and are one indicator of reading difficulty. *Regression path duration* is the sum of all fixation durations from first entering a region until moving to the right of that region (including any regressions) and is another indicator of processing difficulty (Hyöna, Lorch, & Rinck, 2003).

Our study collected both global (at the level of the whole text) and local (at target-word level) measures by monitoring the eye movements of the participants as they read. Global measures of the text reading time, text gaze duration (sum of the gaze duration of all words in the text) and text regressions out were used. Local measures of target reading time, target gaze duration, target regressions out, regression path duration were collected. Fixation duration measures such as text/target gaze duration and text/target reading time are indicators of lexical access (Inhoff & Rayner, 1986; Morton, 1969; Whaley, 1978) and are related to processing and integration of words, and text/target regressions out and regression path duration reflect the ability to understand (Schotter, Tran, & Rayner, 2014). In addition, the accuracy of comprehension was assessed via true-or-false questions about the sentences.

The current study had four goals. The first was to examine the influence of a visual representation on text- and word-level processing. The second goal was to replicate the influence of word frequency at these two levels, as observed in previous studies. The third was to evaluate the influence of visual representation and lexical simplification in dyslexic readers, specifically. The fourth was to observe whether the influence of visual support and word frequency on sentence processing is modulated by other factors commonly known to impact decoding and comprehension, more specifically, vocabulary and print exposure.

These aims were addressed in the following four research questions:

- Research question 1 (RQ1). Does visual representation facilitate sentence processing at text- and word-level?
- Research question 2 (RQ2). Does lexical simplification facilitate sentence processing at text- and word-level?
- Research question 3 (RQ3). Do the effects of visual representation and lexical simplification influence dyslexic readers differently from typically developing readers?

- Research question 4 (RQ4). Are the effects of visual representation and lexical simplification on sentence processing modulated by vocabulary and/or print exposure?

For RQ1 and RQ2, four experimental conditions were created with a 2 × 2 design, resulting from the combination of the inclusion (or not) of supporting visual scenes and word frequency. This results in sentences with a low-frequency target word and without a visual scene, a low-frequency word and a visual scene, a high-frequency word without a scene, and a high-frequency word with a scene. For these research questions, we hypothesized that the image and high-frequency words would facilitate text and word-level processing. We had no hypotheses for interaction effects. We also expected greater accuracy in sentences with an image and sentences with a high-frequency target word. For global level eye-tracking measures, we expected shorter text reading time, shorter text gaze duration, and lower probability of regressions out in these conditions. At the local level (target word), trials with an image and with a high-frequency target word would show shorter target total reading time, shorter target gaze duration, shorter regression path duration, and lower probability of regressions out. Therefore, we expected to find effects of word frequency in line with previous studies, but also an effect of the presence of the image, similar to the recommendations in the easy-to-read guidelines.

In relation to the third aim (RQ3), in addition to a main effect of dyslexia (unrelated in practice to our research aim), we expected an interaction of frequency and image, with greater facilitation of reading for dyslexic readers than for typically-developing readers, since there would potentially be greater room for improvement in lexical access and comprehension for them.

For RQ4, we wanted to determine whether the influence of visual support and word frequency on sentence processing is modulated by other factors commonly known to impact decoding and comprehension, and specifically, vocabulary and print exposure. We hypothesized that the influence of visual support and word frequency on sentence processing would be modulated by vocabulary and print exposure. Thus, we expected to observe a greater effect of vocabulary and print exposure in sentences with an image and high-frequency words on text- and word-level processing. More specifically, we expected readers with poorer vocabulary and less reading experience (print exposure) to benefit most from these adaptations, as shown with greater reductions in reading times and regressions.

Method

Participants

A total of 40 university students (20 dyslexic, 7 males, 13 females; 20 controls, 5 males, 15 females) took part in this study. To assess print exposure, receptive vocabulary, and processing speed, we used the Author Recognition Test, the Peabody Picture Vocabulary Test, and the Rapid Automatized Naming Test respectively, all which are described in the next section. Groups were matched on chronological age, print exposure, and receptive vocabulary, but not on processing speed in number and letter naming (see Table 1).

All participants with dyslexia verified that they had received diagnostic assessments for dyslexia in the past, and were on the disability register at the university. Given the extra provision provided to students with learning disabilities (e.g. grading concessions and extra time on exams), documentation of a positive diagnosis is required by the university in all cases. All participants were native speakers of British English with normal or corrected-to-normal vision. Participants in the dyslexic group were reimbursed £5 for their time, and controls were compensated with participation credits. The study was approved by the School of Psychology Research Ethics Committee at the University of East Anglia (United Kingdom). Before carrying out the study, written informed consent was obtained from all participants, and all were debriefed at the end of the study.

Table 1

Summary of chronological age, RAN, ART, and PPVT scores for participants in the dyslexic and control groups.

	Control (*n* = 20)		Dyslexic (*n* = 20)			
	Mean (*SD*)	Range	Mean (*SD*)	Range	*t* value	Cohen's *d*
Age (years)	19.90 (1.25)	18-22	21.55 (5.50)	18-43	-1.31	0.41
RAN numbers	12.25 (3.09)	8-20	18.10 (5.68)	11-30	-4.05*	1.28
RAN letters	12.45 (2.54)	8-16	19.75 (5.88)	12-31	-5.09*	1.61
ART	9.70 (7.51)	0-30	7.30 (3.95)	1-15	1.27	-0.40
PPVT	101.45 (8.99)	79-117	103.75 (2.33)	82-120	-.75	0.35

Note. Reported scores for RAN tasks and ART are raw scores. Standard scores are reported for PPVT.

Abbreviations: RAN, Rapid Automatized Naming; ART, Author Knowledge Test; PPVT, Peabody Picture Vocabulary Test

*$p < .001$.

Materials

Rapid Automatized Naming Test (RAN). A letter and a number RAN test (Denckla & Rudel, 1976; Norton & Wolf, 2012) were used from the Comprehensive Test of Phonological Processing (CTOPP-2). This test is a strong predictor of reading skills related to processing speed. Participants must respectively name a series of letters or numbers sequentially as quickly as possible. In each task, there are four rows of nine items. Time was recorded with a stopwatch. The score for each task was the total time to complete the task. Mean internal reliability of the CTOPP-2 subtests exceeds .80 (Wagner et al., 2013).

Author Recognition Test (ART). All participants completed individually the ART, which contained 65 literary author names from the Acheson et al. (2008) version of the test, along with 65 additional names, which did not refer to known authors. Participants had to identify the names of authors. All names were listed in alphabetical order of surname. The test is an indicator of reading experience, which is strongly related to reading skill. ART scores have been shown to predict the speed with which university students decode words during reading (Moore & Gordon, 2015). The test was administered on paper, and participants were asked to mark with a cross the names they recognized as authors. They were informed that to mark non-authors was penalized with one point for each error. The administration of the task typically took around 5 minutes. Different studies report internal reliability for the ART ranging from .75 to .89 (Mol & Bus, 2011).

Peabody Picture Vocabulary Test - 4 (PPVT-4). The PPVT-4 (Dunn & Dunn, 2007) was administered to assess receptive vocabulary. It has two forms, of which we used Form A. Participant were asked to select one of four images best illustrating a target word verbally presented by the researcher. The administration of the task typically took around 15 min. The standardization manual reports a reliability range from .89 to .97 in Form A.

Sentence comprehension task. The experimental trials included 60 short sentences with a target word. Each sentence was accompanied by an orally presented inferential comprehension (true-or-false) question. Half the sentences contained a low-frequency target word, while in the other half the target word was replaced with a high-frequency target word of similar meaning. The low- and high-frequency target words were also similar in length ($n \pm 1$). To check the frequency of the word, we used the Word Frequencies in Written and Spoken English, based on the British National Corpus (Leech et al., 2001). Half of the sentences contained an image related to their content. The pictures in the two conditions were below the sentence and centered on the screen.

The combination of picture presence (two versions per sentence) and target-word frequency (two versions per sentence) resulted in four different conditions (with 15 sentences/trials in each condition).

Table 2.

Example of the two versions of a sentence with the low-frequency target word and high-frequency target word (underlined), picture and true-or-false question.

Low-frequency target version	Edward is on the beach <u>scanning</u> the sky because he wants to see a shooting star.

High-frequency target version	Edward is on the beach watching the sky because he wants to see a shooting star.
Picture	
True-or-false question	It was night when Edward was on the beach.

Apparatus

Eye movements were recorded with an EyeLink 1000 eye tracker, sampling at 1000 Hz (SR Research, Ontario, Canada). Viewing distance was 70 cm from eyes to a 45-cm computer monitor, and at this distance, 1.0° of visual angle subtended 1.22 cm. This apparatus allowed recording eye movements through a camera with an infrared tracking system, while the participant was carrying out the experimental task. Head movements were minimised with a chin rest, and eye movements were recorded from the right eye. The sentences were presented in 20-pt. Arial font on a white background, and pictures were in colour.

Design and Procedure

For the sentence processing task, the design was a 2 × 2 × 2 (Picture, Frequency, Group) mixed model, in which Picture and Frequency were within-subject factors, and Group was a between-subjects factor. Participants completed two practice trials, followed by the 60 experimental trials with their true-or-false statement respectively, which were individually presented on a computer screen in random order within each block. Trials were presented in random-ordered blocks of 15 items in the same condition. Each participant was assigned one of four lists, so each participant only read each sentence in one condition, and across participants sentences were presented in all conditions.

First, the participant read a set of instructions with the details of procedure. After the instructions, two examples trials were completed and nine-point calibration and validation procedure was carried out before starting with the first set of critical items. This was repeated before each block so it allowed the participant to rest.

The sentence was presented on the top on the screen. When presented, the visual scene was below the sentence and centered in the screen. When the participant finished reading, s/he pressed the spacebar to switch screen and a true or false statement was presented auditorily. S/he was presented with a fixation cross in the center of the screen while hearing the statement. The participant responded true-or-false by pressing the corresponding key on the keyboard. After each block, the participant was asked to rate the difficulty of comprehending the sentences in the condition, from 1 to 5, with 5 being the hardest.

The testing session for each participant lasted around 45 minutes in total, of which 20 minutes corresponded to the experimental task. The tests were delivered in the following order for each participant before the experimental task: ART, RAN digits, RAN letters and PPVT.

Data Screening and Analysis

Fixations less than 80 ms and longer than 1200 ms were excluded from the dataset. Data from each sentence were revised. Those not recorded or with excessive blinks were excluded from the analyses, resulting in data loss of 1.21%.

Data for each eye-movement measure greater than 3 SDs from the mean of the respective block of each variable were defined as outliers. Outliers were replaced with the mean of that variable (McCartney et al., 2006), which were obtained via standardised values. We found 4.22% of outliers, and this resulted in the exclusion of a total of 5.43% of the data.

We reported global and local measures, which respectively related to reading behaviour during the reading of the sentence or of the target word of each sentence. We included three text-level measures (text reading time, text gaze duration, and probability of regressions out) and four target-word-level measures (target reading time, target gaze duration, probability of regressions out, and regression path duration). To calculate the probability of text regressions out, we summed all probabilities of regressions out on the sentence. Then, we divided each sentence by the number of words of each one. Finally, we calculated the mean of the probability of target regressions out in each block.

We analysed text/target reading time, text/target gaze duration, probability of text regressions out, and regression path duration data using mixed ANOVAs (Picture × Frequency × Group) across subjects (F_1) and items (F_2). Text gaze duration and probability of text regression out data met the normality, homoscedasticity, and sphericity assumptions. Text/target reading time, target gaze duration, and regression path duration were log-transformed to meet these assumptions.

Nonparametric analyses across subjects and items were performed on accuracy and target regressions out. We used Wilcoxon Signed-Rank Test for paired samples and Mann-Whitney U Test for independent samples. For these variables, main effects of Picture and Frequency by subjects were assessed using Wilcoxon Signed-Rank Test (Z_1) and of Group with the Mann-Whitney U Test (U_1). Main effects of Picture, Frequency, and Group by items were assessed using the Wilcoxon Signed-Rank Test (Z_2).

Following the analyses of the effects of Picture, Frequency, and Group, we analysed the possible influence of ART and VOC as follows: first, we conducted analyses of covariance (ANCOVAs) in which each control factor was covaried separately in all variables. Second, we chose the variables that covaried with ART and/or VOC (Target Reading Time, Target Gaze Duration and Text Reading Time). And third, due to the non-compliance with the assumption of equality of regression slope in the ANCOVAs analyses, we conducted data analysis using mixed ANOVAs (Group X Frequency X Picture X ART/VOC) across subjects (F_1) and items (F_2). We used paired and independent samples *t* tests to compare the means of frequency x ART/VOC interactions. To convert the ART and VOC covariables into categorical variables, we calculated median splits within each group.

We report η^2_p, *r*, and *Cohen's d* for the effect sizes (Field, 2009).

Results

Accuracy

There were no significant main effects of Picture $Z_1 = -0.55$, $p = .582$, $r = .03$ (M = 84, SD = 8 for No Picture; M = 83 SD = 9 for Picture), Frequency $Z_1 = -1.52$, $p = .128$ (M = 82, SD = 9 for Low frequency; M = 85, SD = 8 for High frequency), $r = -0.18$, or Group $U_1 = -1.57$, $p = .117$, $r = .19$ (M = 84, SD = 8 for Controls; M = 82, SD = 5 for Dyslexics) on accuracy, although Z_2 analyses showed significant main effects of Picture $Z_2 = -2.06$, $p < .05$, $r = .26$ and Frequency $Z_2 = -2.09$, $p < .05$, $r = -.51$.

Participants' Perceptions of Text and Question Difficulty

In general, participants evaluated sentences as easy to understand (M = 2.38, SD = 0.88), although control participants found them easier than dyslexics, M = 2.04, SD = 0.88 for Controls; M = 2.71, SD = 0.74 for Dyslexics; $t(38) = -2.62$, $p < .05$, $d = -0.82$. Furthermore, all participants scored sentences with an image easier to understand than those without image, M = 2.24, SD = 0.95 and M = 2.51, SD = 0.94 respectively, $t(39) = 2.43$, $p < .05$, $d = 0.78$. No differences were observed between sentences with low- and high-frequency words, M = 2.31, SD = 0.90 and M = 2.44, SD = 0.96, respectively, $t(39) = -1.30$, $p = .20$, $d = -0.42$.

Text Measures

Text Reading Time. Initial ANOVAs on text reading time (without ART or Vocabulary) showed significant main effects of Frequency $F_1(1,38) = 10.42$, $p < .01$, $\eta^2_p = .22$; $F_2(1,59) = 431.55$, $p < .001$, $\eta^2_p = .88$ (M = 4678, SD = 1540 for Low frequency; M = 4422, SD = 1386 for High frequency) and Group $F_1(1,38) = 13.47$, $p < .01$, $\eta^2_p = .26$; $F_2(1,59) = 40.58$, $p < .001$, $\eta^2_p = .41$ (M = 3820, SD = 885 for Controls; M = 5279, SD = 1542 for Dyslexics). Participants spent more time reading sentences with a low-frequency word, and participants with dyslexia spent more time reading than controls. The main effect of Picture was non-conclusive (significant F_1 and non-significant F_2), and no interaction effects were significant (see supplementary Table s1.1 for all means and standard deviations, and Table s1.2 for the full ANOVA).

We then performed two ANCOVAs including ART and Vocabulary as covariates. There were no significant main or interaction effects involving ART. In the ANCOVA including Vocabulary, there was an interesting interaction of Frequency and Vocabulary, $F(1,37) = 7.61$, $p < .01$, $\eta^2_p = .17$. Unfortunately, this interaction effect is indicative of unequal regression slopes between groups (see Table s1.3).

To further explore the effects of Vocabulary and the other factors, a subsequent ANOVA with median-split group membership respectively (high vs low Vocabulary) was carried out. This ANOVA confirmed main effects of Frequency and Group, but not the interaction of Frequency x Vocabulary (see Table s1.4).

Text Gaze Duration. An initial ANOVA (without ART or VOC) showed significant main effects of Picture $F_1(1,38) = 28.44$, $p < .001$, $\eta^2_p = .43$; $F_2(1,59) = 39.03$, $p < .001$, $\eta^2_p = .40$ (*M* = 3097, *SD* = 730, for No Picture; *M* = 2820, *SD* = 596 for Picture), and Group $F_1(1,38) = 10.95$, $p < .01$, $\eta^2_p = .23$; $F_2(1,59) = 587.79$, $p < .001$, $\eta^2_p = .91$ (*M* = 2657, *SD* = 472 for Controls; *M* = 3261, *SD* = 666 for Dyslexics). Sentences without a picture had longer reading times than sentences with a picture, and participants with dyslexia spent more time reading sentences compared to controls (see Table s1.1). No other main effects or interactions were significant (see Table s2.1). ANCOVAs including ART or Vocabulary respectively showed no significant main or interaction effects involving these variables, and no further analyses were therefore pursued (see Table s2.2).

Text Regressions Out. There was a significant main effect of Frequency $F_1(1,38) = 7.59$, $p < .01$, $\eta^2_p = .17$; $F_2(1,59) = 6.20$, $p < .05$, $\eta^2_p = .10$ (*M* = 0.10, *SD* = 0.05 for Low frequency; *M* = 0.09, *SD* = 0.04 for High frequency), in the ANOVA without ART or Vocabulary. Sentences with a low-frequency word had more regressions than sentences with a high-frequency word (see Table s1.1). No other effects were significant in this analysis (see Table s3.1), nor were the main or interaction effects of ART or Vocabulary in the subsequent ANCOVAs (see Table s3.2).

Target-Word Measures

Target Reading Time. ANOVAs without ART or Vocabulary showed that main effects of Picture, Frequency, and Group were all significant. Sentences without a picture presented longer reading time than sentences with one, $F_1(1,38) = 8.33$, $p < .01$, $\eta^2_p = .18$; $F_2(1,59) = 14.04$, $p < .001$, $\eta^2_p = .19$ (*M* = 502, *SD* = 189 for No Picture; *M* = 454, *SD* = 175 for Picture). The low-frequency words had higher reading times than high-frequency words, $F_1(1,38) = 53.44$, $p < .001$, $\eta^2_p = .58$; $F_2(1,59) = 90.51$, $p < .001$, $\eta^2_p = .61$ (*M* = 556, *SD* = 241 for Low frequency; *M* = 400, *SD* = 128 for High frequency). Dyslexic participants had longer reading time compared to controls, $F_1(1,38) = 9.90$, $p < .01$, $\eta^2_p = .21$; $F_2(1,59) = 127.45$, $p < .001$, $\eta^2_p = .68$ (*M* = 403, *SD* = 117 for Controls; *M* = 553, *SD* = 192 for Dyslexics; see Tables s4.1 and s4.2).

In the ANCOVA including ART, there were a main effect of ART $F(1,37) = 14.47$, $p < .01$, $\eta^2_p = .28$, and significant interactions of Picture x ART $F(1,37) = 4.52$, $p < .05$, $\eta^2_p = .11$, and Frequency x ART $F(1,37) = 7.97$, $p < .01$, $\eta^2_p = .18$ (Table s4.3). In the other ANCOVA including Vocabulary, there was a main effect of Vocabulary, $F(1,37) = 5.59$, $p < .05$, $\eta^2_p = .13$, and a significant interaction Frequency × Vocabulary $F(1,37) = 7.77$, $p < .01$, $\eta^2_p = .17$. (see Table s4.3). As with text measures, these interactions were indicative of unequal slopes, but of interest and were further explored in ANOVAs with median-split groups of ART and Vocabulary, respectively.

In the ANOVA including ART, the main effects of Picture, Frequency and Group remained significant, as did the main effect of ART and the Frequency × ART interaction, but Picture x ART did not (see Table 3). Only the paired comparison of low vs. high frequency word in low ART was significant $t_1(18) = 2.31$, $p < .05$, $d = 0.22$.; $t_2(43) = -6.60$, $p < .001$, $d = 1.40$ (see Figure 1). And when Vocabulary was included in another ANOVA, the main effects of Frequency and Group, and the interaction Frequency × Vocabulary remained significant, but the main effect of Vocabulary did not (see Table 3). Only the paired comparison of low vs. high frequency word in low Vocabulary was significant $t_1(21) = 3.91$, $p < .01$, $d = 0.24$; $t_2(56) = 9.69$, $p < .001$, $d = 1.71$ (see Figure 2).

Table 3.

Effects of ART and Vocabulary in Target Reading Time and Target Gaze Duration.

Target Reading Time	
ART	
Picture	F_1 (1,36) = 9.53, $p < .01$, $\eta^2_p = .21$; F_2 (1,27) = 7.14, $p < .05$, $\eta^2_p = .21$
Frequency	F_1 (1,36) = 64.67, $p < .001$, $\eta^2_p = .64$; F_2 (1,27) = 46.17, $p < .001$, $\eta^2_p = .63$
Group	F_1 (1,36) = 10.57, $p < .01$, $\eta^2_p = .23$; F_2 (1,27) = 71,75, $p < .001$, $\eta^2_p = .73$
ART	F_1 (1,36) = 6.23, $p < .05$, $\eta^2_p = .15$; F_2 (1,27) = 27.52, $p < .001$, $\eta^2_p = .51$
Picture x ART	F_1 (1,36) = 4.97, $p < .05$, $\eta^2_p = .12$; F_2 (1,27) = 1.06, $p = .313$, $\eta^2_p = .04$
Frequency x ART	F_1 (1,36) = 8.61, $p < .01$, $\eta^2_p = .19$; F_2 (1,27) = 12.48, $p < .01$, $\eta^2_p = .32$
Vocabulary	
Picture	F_1 (1,36) = 8.32, $p < .01$, $\eta^2_p = .19$; F_2 (1,27) = 8.05, $p < .01$, $\eta^2_p = .23$
Frequency	F_1 (1,36) = 55.56, $p < .001$, $\eta^2_p = .61$; F_2 (1,27) = 50.46, $p < .001$, $\eta^2_p = .65$
Group	F_1 (1,36) = 9.28, $p < .01$, $\eta^2_p = .21$; F_2 (1,27) = 98.31, $p < .001$, $\eta^2_p = .79$
Vocabulary	F_1 (1,36) = 0.94, $p = .338$, $\eta^2_p = .03$; F_2 (1,27) = 9.66, $p < .01$, $\eta^2_p = .26$

Frequency x Vocabulary	F_1 (1,36) = 6.51, $p < .05$, $\eta^2_p = .15$; F_2 (1,27) = 12.24, $p < .01$, $\eta^2_p = .31$
Target Gaze Duration	
ART	
Picture	F_1 (1,36) = 5.46, $p < .05$, $\eta^2_p = .13$; F_2 (1,21) = 1.57, $p = .224$, $\eta^2_p = .07$
Frequency	F_1 (1,36) = 27.41, $p < .001$, $\eta^2_p = .43$; F_2 (1,21) = 15.99, $p < .05$, $\eta^2_p = .43$
Group	F_1 (1,36) = 5.12, $p < .05$, $\eta^2_p = .13$; F_2 (1,21) = 15.17, $p < .05$, $\eta^2_p = .42$
ART	F_1 (1,36) = 3.03, $p = .09$, $\eta^2_p = .08$; F_2 (1,21) = 16.48, $p < .05$, $\eta^2_p = .44$
Frequency x ART	F_1 (1,36) = 4.13, $p = .05$, $\eta^2_p = .10$; F_2 (1,21) = 0.68, $p = .42$, $\eta^2_p = .03$

Note. Abbreviation: ART, Author Knowledge Test; Vocabulary, Peabody Picture Vocabulary Test (PPVT).

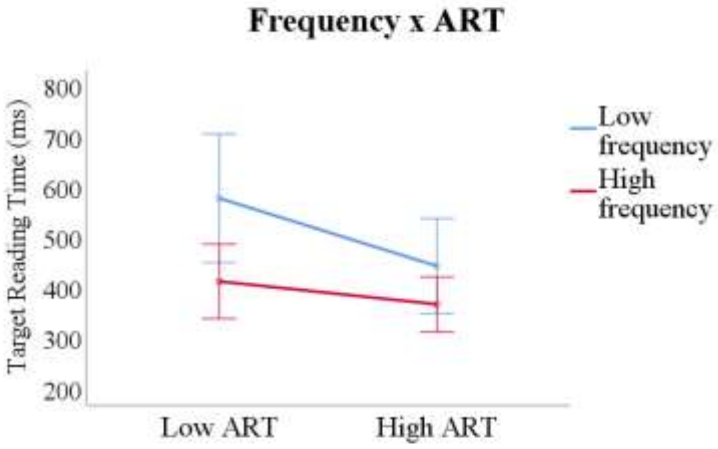

Figure 1. Interaction between Frequency and ART.

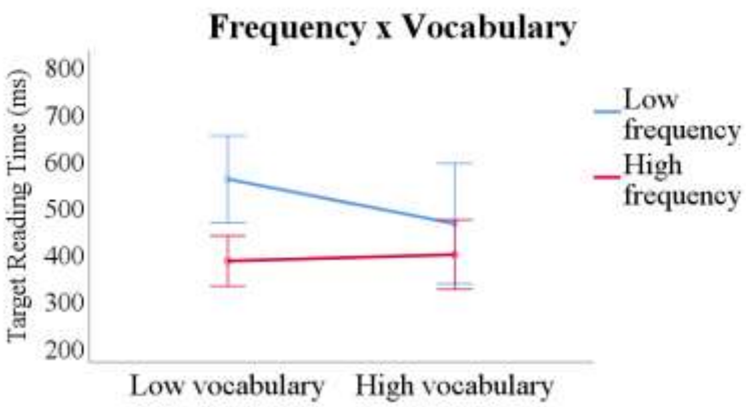

Figure 2. Interaction between Frequency and Vocabulary.

Target Gaze Duration. The ANOVA without ART or Vocabulary showed significant main effects of Picture, Frequency, and Group (see Table s5.1). Sentences without a picture had longer target gaze duration times than sentences with a picture, $F_1(1,38) = 4.91$, $p < .05$, $\eta^2_p = .11$; $F_2(1,58) = 10.91$, $p < .01$, $\eta^2_p = .16$ (*M* = 285, *SD* = 71 for No Picture; *M* = 267, *SD* = 60 for Picture). The low-frequency words had longer target gaze duration than high-frequency words, $F_1(1,38) = 23.67$, $p < .001$, $\eta^2_p = .38$; $F_2(1,58) = 39.20$, $p < .001$, $\eta^2_p = .40$ (*M* = 296, *SD* = 79 for Low frequency; *M* = 255, *SD* = 50 for High frequency). Participants with dyslexia had longer target gaze duration compared to controls, $F_1(1,38) =$

5.42, $p < .05$, $\eta^2_p = .13$; $F_2(1,58) = 44.72$, $p < .001$, $\eta^2_p = .44$ ($M = 258$, $SD = 57$ for Controls; $M = 294$, $SD = 57$ for Dyslexics; see Table s4.1).

When ART was included as a covariate in the ANCOVA, there was a main effect of ART $F(1,37) = 6.92$, $p < .05$, $\eta^2_p = .16$, and a significant interaction between Frequency × ART $F(1,37) = 5.75$, $p < .05$, $\eta^2_p = .14$ (see Table s5.2). The ANCOVA with Vocabulary as covariate did not show any significant main effects or interactions involving Vocabulary (see Table s5.3).

When ART was included in the 2 × 2 × 2 ×2 (Picture × Frequency × Group × median-split ART group) ANOVA, the mains effects of Frequency and Group remained significant, but the main effects of Picture and ART, and interaction Frequency × ART did not (see Table 3).

Target Regressions Out and Regression Path Duration. Regression out showed only a significant main effect of Frequency $Z_1 = -2.84$, $p < .01$, $r = .22$, $Z_2 = -3.62$, $p < .001$, $r = .33$ ($M = 0.22$, $SD = 0.12$ for Low frequency; $M = 0.17$ $SD = 0.09$ for High frequency). Low-frequency words had higher probability of regression than high-frequency words (see Table s4.1 and s6.1).

Regression path durations showed significant main effects of Picture and Frequency. Sentences without a Picture had longer duration of regressions than sentences with it, $F_1(1,38) = 12.70$, $p < .01$, $\eta^2_p = .25$; $F_2(1,58) = 11.24$, $p < .01$, $\eta^2_p = .16$ ($M = 571$, $SD = 181$ for No Picture; $M = 496$, $SD = 177$ for Picture). The low-frequency words had longer regression paths than high frequency words, $F_1(1,38) = 16.19$, $p < .001$, $\eta^2_p = .30$; $F_2(1,58) = 12.18$, $p < .01$, $\eta^2_p = .17$ ($M = 586$, $SD = 213$ for Low frequency; $M = 481$, $SD = 155$ for High frequency; see Tables s4.1 and s7.1).

ANCOVAs with ART and Vocabulary on regression path durations showed not significant interaction effects involving any of these variables (see Table s7.2).

Discussion

In this study, we investigated sentence processing in readers with dyslexia, and specifically, adaptations, which follow *easy-to-read* guidelines, including both visual support and lexical simplification. Our findings suggest that visual support with text-related images aides the initial processing of words in the sentence, allowing readers to predict or anticipate upcoming sentence content. Lexical simplification facilitated processing at the both the text- and word-levels. We also explored the impact of two key control variables (vocabulary and print exposure). Our findings showed that participants with lower vocabulary and lower print exposure benefited the most from lexical simplification. Lower vocabulary and lower print exposure are common characteristics of individuals with dyslexia. In this study, we used eye tracking, and we included three text-level measures (text reading time, text gaze duration and probability of regression) and four target-word measures (target reading time, target gaze duration, probability of regression, and regression path duration). Reading time and gaze duration are indicators of lexical access and integration (Inhoff & Rayner, 1986; Morton, 1969; Whaley, 1978), while regressions and regression path durations are indicative of more global comprehension difficulty (Schotter et al., 2014).

The first aim of the study (RQ1) was to examine the influence of visual support on text- and word-level processing. Many previous studies did not observe a positive effect of visual support on comprehension, despite using a variety of formats and in a range of different disorders. Recall that Poncelas and Murphy (2007) evaluated understanding with symbols, Dye et al. (2007) used photographs, and Yaneva (2016) used images. We did not find consistent effects of a visual image on reading accuracy either, although participants did judge these texts as easier to read. As for eye-tracking, we hypothesized that visual support and high-frequency words would facilitate both text- and word-level processing. At the text level, we expected to observe shorter text gaze duration and shorter text reading time, and lower probability of regression. At the word level, trials with an image would show shorter target gaze duration and shorter target reading time, lower probability of regression, and shorter regression path durations. Our results indicated that the presence of an image facilitated recognition of words in the text (lexical access/integration), as indicated by shorter text and target gaze durations. The role of visual support in facilitating global or overall comprehension was less clear. There was no reduction in the probability of regression at the text level or in probability of regression (out) of the target word, although visual support did result in shorter target regression path durations. Therefore, our hypotheses were partially supported.

These results indicate that visual support assists more in the initial processing of words in the sentence, likely by allowing readers to predict either actual lexical items or through activation of semantic content, which then facilitates lexical access. Since our visual support provides a broad depiction of the meaning of the sentence, we assumed that our images would support overall comprehension, which did not happen. Thus, the eye-tracking data suggest that images assist in the creation of a mental representation, which then when combined together with the linguist content of the sentence, serve as top-down constraints for the processing of the target word (Huettig et al., 2011; Pickering & Gambi, 2018).

The second aim of the study (RQ2) was to examine the influence of word frequency on text- and word-level processing. Data from many previous studies support the idea that higher frequency words are processed more quickly and efficiently (e.g. Ashby et al., 2005; Hyönä & Olson, 1995; Rayner & Duffy, 1986). We hypothesized that high-frequency words would result in facilitation at both the text- and word-level, as compared to low-frequency words. At the text level, results showed shorter text reading time and lower probability of regression in sentences with a high-frequency target word. In contrast, we did not find shorter text gaze duration. Therefore, our hypotheses were again only partially supported. Thus, these results indicate that lexical adaptation (of a single word) facilitated comprehension overall, and therefore, reduced the difficulty of sentence processing, again overall. At the word level, trials with a high-frequency target word were expected to show shorter target gaze duration, shorter target reading time, lower probability of regression, and shorter regression path duration. We did find shorter target gaze duration, shorter target reading time, lower probability of regression, and shorter regression path duration with high-frequency target words. Therefore, our hypotheses were supported at the word level. These results are in line with previous studies that focused on processing of high- and low-frequency words, and in contrast to visual support, text adaptation via high-frequency words is a bottom-up process. That is, it facilitates lexical access to particular words (as indicated by the target eye-tracking measures), but it also has important effects on facilitating overall sentence comprehension (as shown by text-level eye-tracking measures).

The third aim (RQ3) was to evaluate the influence of visual support and lexical simplification on individuals with dyslexia, and to compare them to typically-developing controls. We hypothesized that there would be a main effect of group, with longer reading times and higher probability of regression in the dyslexic group, and that visual support and lexical simplification would benefit dyslexic readers to a greater extent (i.e. reducing the difference between groups). With respect to eye tracking measures at the text-level, we expected longer text gaze duration, longer text reading time, and a greater probability of regressions in dyslexics compared to controls. At the word-level, we expected longer target reading time, longer target gaze duration, higher probability of regression, and longer regression path durations in dyslexics. These predictions were partially supported. Our results showed longer reading time and gaze durations at both the text and word levels, suggesting that readers with dyslexia had slower lexical access, consistent with previous research (e.g. Hyönä & Olson 1995; Jones et al., 2007; Rello et al., 2013). However, we did not find group differences in the probability of regression. It seems that once word meaning is accessed, comprehension within the context of the sentence is not impaired in dyslexia. It is important to keep in mind that our dyslexic participants were all university students, and therefore, have achieved a good level of reading comprehension, some even possibly achieving what is referred to as “compensated” dyslexics.[1] It is also important to note that we found no interactions in any of the eye-tracking measures between visual support, lexical simplification, and group. This strongly indicates that these adaptations do not facilitate reading for dyslexic participants more-or-less than they help the control participants.

The fourth aim (RQ4) was to determine whether the influence of visual support and lexical simplification was modulated by vocabulary and print exposure, two alternative variables linked with dyslexia. Thus, we expected greater effects of the adaptations on participants with lower vocabulary and less print exposure. This expectation turned out to be partially correct for word frequency, but not for visual support. We found a differential effect on target-word processing modulated by vocabulary and print exposure: differences between target reading times of high- and low-frequency target words were significant only for participants with lower vocabulary and less print exposure. In contrast, there was no differential effects at the text-level or in the absence or presence of visual support at both levels.

In summary, we have found (1) that visual support and lexical simplification (i.e. easy-to-read adaptations) have a positive impact on processing difficulty in reading, and (2) that they do not have substantial impact on reading accuracy. Most researchers would likely assume that visual scenes and the increased use of high-frequency words would impact

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[1] The effect sizes of the main effect of group on the text-level reading time measures were approximately .25 (i.e. diagnostic status accounted for about one-quarter of the variance in reading times). The mean group difference in text (total) reading time was approximately one and a half seconds, which translates to about 25% longer. Thus, it took dyslexic participants 25% more processing time to achieve equal comprehension accuracy. Increased re-reading is commonly regarded as the most frequent reading strategy employed by individuals with dyslexia (Simmons & Singelton, 2000).

sentence processing by facilitating overall comprehension and lexical access, respectively. Our data support these general assertions, but also, that both visual support and higher frequency words facilitate semantic access to word meaning itself. The visual support (i.e. a scene) seems to provide a visual context, which provides a mental representation (a situation schema), which directly relates to the linguistic (sentence) content. This, in turn, can constrain and facilitate lexical access and word meaning via top-down semantic activation(s). Lexical simplification, on the other hand, directly facilitates lexical access for individual words as they are encountered in sentential context. These more-or-less direct bottom-up effects were especially pronounced in individuals with lower vocabulary and less print exposure, for whom lower frequency words may be less familiar. To our surprise, our results did not show the adaptations to be of greater help to individuals with dyslexia. It is possible that this result is because of some aspect of our particular sample of dyslexics. However, given the mixed results in the literature, a positive effect of adaptations on online processing is an important result, even if the take home message is that the adaptations also benefit typically developing adults as well.

Our study also provides some practical implications for future research in the field and for validation procedures of easy-to-read texts. Traditionally, readers perceptions of text difficulty are used as indicators of the impact of text simplification (Asociación Española de Normalización, 2018; Cerga-Pashoja et al, 2019; Karreman et al., 2007). Although our participants did appear to notice the effect of providing visual support, they were not aware of the potential impact of word frequency. Our data suggest that subjective self-report measures are of use in the field, but also that they should be included together with other objective indicators of cognitive and linguistic processing cost when feasible.

The current study had several limitations, which should be kept in mind when interpreting the results. The first and most important concerns the sample of dyslexics. Our participants were all university students, and thus, were high achieving dyslexics. Many individuals with dyslexia do not go on to higher education, and therefore, our findings may not generalize to the full population of dyslexics. However, the differences should be even larger in non-university recruited dyslexic adults. We recommend that this study be extended using both a larger sample of participants, and individuals from different educational levels, ideally recruited from the community rather than the university. A second limitation of the study concerns the role of vocabulary and print exposure. We assessed print exposure using the author recognition task, which admitted even by the creators of that task, is a very rough proxy for overall levels of reading experience. In addition, the ANCOVAs, which included these alternative variables, were likely to be underpowered given the numbers of participants we tested. Therefore, results relating to vocabulary and print exposure should be interpreted with caution.

A third limitation of the study has to do with the type of image. There are various types of pictorial illustrations that influence text processing in different ways. Representational pictorial illustrations, which we use in our study, tend to have moderate benefits, while transformational illustrations tend to have substantial benefits in word processing (Carney & Levin, 2002). It would be interesting to analyse the effects of different types of images to find out whether the same occurs in sentence processing. Another aspect to take into account is that our study presented short and simple sentences to read, except for the target words, which varied in frequency, because we wanted to observe the impact of target words on sentence processing at the text- and word-level. Future lines of research should be aimed at observing whether these same results would be found with longer or more complex sentences, or even in paragraph-type texts. The effects of visual support and lexical simplification in word processing may be more pronounced. It will also be important to evaluate the effects that more complex tasks have on other cognitive factors, such as working memory or executive function (Smith-Spark, 2018; Smith-Spark & Gordon, 2019). Finally, within group variability was not considered in this study: differences in reading skill, working memory, or executive function across individuals with dyslexia could result in different levels of facilitation.

Conclusions

This is the first study explore the effect of the two main adaptations for *easy-to-read* guidelines in individuals with dyslexia. Our results indicated that visual support and lexical simplification reduces processing difficulty in reading. They also provide empirical support for multiple avenues in which to modify written materials in order to facilitate processing for all readers, including those with dyslexia, and especially, those with lower vocabulary and less reading experience. These findings open up a large range of possibilities in which to assist individuals with dyslexia from navigating everyday life (e.g. in job applications or driving tests) to achieving their academic potential (e.g. by creating dyslexia friendly exams and assessments). At present, there is not sufficient evidence to demonstrate that the easy-to-read adaptations benefit individuals with dyslexia more than non-dyslexic individuals. However, future studies, employing more representative samples of dyslexics may in fact show a greater benefit the easy-to-read suggestions, a possibility that is further supported by our vocabulary and print exposure findings.

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