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A dual-route perspective on eye movements of dyslexic readers

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Abstract

This study assessed eye movement abnormalities of adolescent dyslexic readers and interpreted the findings by linking the dual-route model of single word reading with the E-Z Reader model of eye movement control during silent sentence reading. A dysfunction of the lexical route was assumed to account for a reduced number of words which received only a single fixation or which were skipped and for the increased number of words with multiple fixations and a marked effect of word length on gaze duration. This pattern was interpreted as a frequent failure of orthographic whole-word recognition (based on orthographic lexicon entries) and on reliance on serial sublexical processing instead. Inefficiency of the lexical route was inferred from prolonged gaze durations for singly fixated words. These findings were related to the E-Z Reader model of eye movement control. Slow activation of word phonology accounted for the low skipping rate of dyslexic readers. Frequent reliance on sublexical decoding was inferred from a tendency to fixate word beginnings and from short forward saccades. Overall, the linkage of the dual-route model of single word reading and a model of eye movement control led to a useful framework for understanding eye movement abnormalities of dyslexic readers.

Keywords

Developmental dyslexia; Dual-route model of reading; Eye movement control; E-Z Reader; Lexical route; Sublexical route

1. Introduction

A substantial number of studies have documented that dyslexic readers in orthographies more regular than English suffer from a pervasive and persistent reading speed deficit, but much less from the reading accuracy problem which is characteristic for English dyslexic readers (e.g., Dutch: Van den Bos, 1998; Yap & Van der Leij, 1993; German: Wimmer, 1993; Italian: Zoccolotti et al., 1999; Spanish: Gonzalez & Valle, 2000; Norwegian: Lundberg & Hoien, 1990; Greek:Porpodas, 1999). The reasons for the rather accurate reading performance simply follow from the nature of these orthographies: first, there are rather few irregular words which would require knowledge of how specific letter strings are pronounced. Second, grapheme–phoneme rules correspond to the correct phonological forms in the majority of cases. These features may raise doubts on the usefulness of the well-known dual-route model of visual word processing (DRC, Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) for regular orthographies (Share, 2008). Specifically, one may question the need for the lexical route to word phonology (via orthographic word recognition units) as this route was originally introduced to provide correct readings of the irregular words of English (e.g., Coltheart, Curtis, Atkins, & Haller, 1993). However, as

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pointed out by Share (2008), the more important distinction captured by the dual-route architecture is the one between familiar and unfamiliar visual words and this distinction – different from the regular–irregular distinction – applies to both regular and irregular orthographies. In dual-route theorizing, the remarkable speed and effortlessness with which familiar visual words are read, is taken to reflect lexical route processes, whereas the well-documented word length effect in the case of unfamiliar visual words is taken to reflect serial sublexical grapheme–phoneme conversion in order to access phonology and meaning.

From this perspective, one source of the mentioned reading speed problem of dyslexic readers in regular orthographies may be an impoverished orthographic lexicon (e.g., Reitsma, 1983). Support for this and additional dual-route explanations of the dyslexic reading speed problem was indeed provided by a recent study from our group with German dyslexic readers (Bergmann & Wimmer, 2008). This study used a phonological lexical decision task (i.e., *Does xxx sound like a real word*?) and presented familiar (e.g., *Taxi*) and unfamiliar letter strings (e.g., *Taksi*) of existing phonological forms and of nonwords (e.g., *Tazi*) and an orthographic lexical decision task (i.e., *Is xxx correctly written*?) assessed whether the supposedly familiar orthographic forms were indeed familiar. From the dual-route perspective, familiarity amounts to orthographic word representations and availability of such representations was inferred from the correct response patterns in the orthographic task (e.g., from YES to *Taxi* and NO to *Taksi*). Dyslexic readers exhibited a marked orthographic deficit on this task with only about 60% correct decisions (controls: close to 90%). With respect to speed impairments, a critical finding was that dyslexic readers exhibited markedly slower phonological lexical decisions for orthographically unfamiliar words compared to orthographically familiar words suggesting an important role of the orthographic lexicon for reading speed. However, frequent unavailability of orthographic word recognition units was not the only source of the dyslexic speed deficit in the phonological task. Dyslexic readers exhibited slow phonological lexical decisions (compared to controls) even for orthographically known words. This pointed to inefficiency of the lexical route and was interpreted as speed impaired access from orthographic to phonological word representations. Furthermore, our dyslexic readers exhibited slow phonological lexical decision on pseudohomophones and nonwords which must have been unfamiliar for both groups. This was interpreted as inefficient functioning of the sublexical route and was assumed to arise from slow access from graphemes to phonemes.

Obviously, phonological lexical decisions are rather distant from visual word processing in natural situations so that one may question, whether the mentioned dual-route account of the dyslexic speed deficits in the phonological lexical decision task does apply to silent reading of sentences. Of specific interest will be whether dyslexic readers will exhibit eye movement evidence for speed impaired processing even of high frequency words for which availability of whole-word recognition units in the orthographic lexicon can be assumed. One may reason that the slowed phonological lexical decisions in response to such words – observed by Bergmann and Wimmer – were due to the specific demands of the phonological lexical decision task which required access to word phonology and explicit phonological lexical decision. In a broader perspective, one could argue that the phonological lexical decision task is biased towards support of the dominant phonological deficit explanation of dyslexia (e.g., Snowling, 2000). No such bias is expected from eye movements during silent sentence reading.

The present dual-route perspective on dyslexic eye movements may also be of interest for models of eye movement control during reading. Models such as the E-Z Reader model (Pollatsek, Reichle, & Rayner, 2006; Reichle, Rayner, & Pollatsek, 2003) and the SWIFT model (Engbert, Nuthmann, Richter, & Kliegl, 2005; Kliegl & Engbert, 2003) include a word identification component, which – in rough analogy to the lexical route of the dual-

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route model – differentiate between orthographic whole-word recognition and access to the phonological word form and meaning. Different from dual-route models there is no explicit provision for the possibility – occurring quite frequently for dyslexic readers – that orthographic word recognition may fail.

Of interest for expectations on eye movement abnormalities of dyslexic readers is how the stages of word identification are linked to control processes which move visual attention and the eyes from word to word. To investigate the link between word recognition and the control of eye movements and attention, we relied on the E-Z Reader model, because – like dual-route models of visual word recognition – the model processes one word at a time (by strictly serial shifts of attention from one word to the next). The SWIFT model processes up to four words simultaneously. To illustrate relevant assumptions of the E-Z Reader model, for the present study, let us assume that both the eyes and visual attention are focused on word *n* and word identification processes (i.e., orthographic recognition and access to word phonology) are performed. The model assumes that programming of the saccade to word $n + 1$ begins with successful orthographic recognition (termed *familiarity check*; Pollatsek et al., 2006) and movement of attention (not necessarily of the eyes) to word $n + 1$ is triggered by accessing word phonology (and meaning; termed *lexical completion*). Let us now consider the case of a competent reader with quick orthographic recognition and fast access to word phonology. In this case, the attentional spotlight moves to word $n + 1$ soon after orthographic recognition and processing of word $n + 1$ begins. If saccade programming is still in an early (i.e., labile) stage, when the familiarity check of word $n + 1$ is completed, then saccade programming for word $n + 1$ will be canceled and replaced by programming a saccade to word $n + 2$. This feature of the model explains the frequent word skipping of competent readers. Let us now consider the case of a dyslexic reader which exhibits successful quick orthographic recognition of word *n*, but abnormally slow access to word phonology (i.e., slow lexical completion). This would result in late movement of attention to word $n + 1$ during fixating word *n* and, therefore, no skipping of word $n + 1$ will occur, because saccade programming has reached its non-labile stage. An even more consequential problem would arise when, due to absence of an entry in the orthographic word lexicon, even the first stage of word identification fails. In this case there will be no programming of a saccade to the next word. Instead, serial decoding of the unfamiliar visual word – according to dual-route models – may result in left to right movement of attention over the letter string or in execution of short saccades within the currently fixated word (i.e., frequent refixations). The manifestation of this would be a marked effect of word length (i.e., number of letters) on single fixation duration or on number of refixations per word.

For programming of saccades, E-Z Reader assumes a preferred saccade length of 7 letter spaces and a modification of this length to the center of the upcoming word, which constitutes the optimal viewing position. The often less than optimal adjustment of the preferred saccade length explains the systematic “overshoots” for short and the “undershoots” for long words (McConkie, Kerr, Reddix, & Zola, 1988). For the dyslexic readers one can consider two possibilities. One is that saccade programming for dyslexic readers is similar to that of typical readers, that is, conforms to a preferred saccade length with adjustments to the center of the upcoming word. In this case one would not expect a difference in the initial fixation location of the dyslexic and the typical readers, but frequent regressions back to the word beginning (i.e., within-word regressions) due to frequent failure of orthographic word recognition. Alternatively, frequent orthographic recognition failures may have resulted in a general tendency to target the beginnings of words. Studies with German and Italian dyslexic children provided evidence for the latter possibility (De Luca, Borrelli, Judica, Spinelli, & Zoccolotti, 2002; MacKeben et al., 2004). Of specific interest is the study by MacKeben et al. which presented words of varying lengths right of a fixation point. Typically reading children linearly adjusted saccade length to the length of the word, whereas the dyslexic children largely failed to do so. It will be of interest whether the present, more advanced dyslexic readers in a silent reading task will also exhibit this pattern.

The present study examined the aforementioned expectations – derived from the dual-route model and the E-Z Reader model – for the eye movements of dyslexic German-speaking adolescents with a long history of a severe reading speed problem. They read silently the Potsdam Sentence Corpus (144 sentences with nearly 1000 words; see Kliegl, Grabner, Rolfs, & Engbert (2004) for details) for which the Potsdam group collected eye movement data from large samples of typical readers (e.g., Kliegl, Nuthmann, & Engbert, 2006). The availability of frequency and predictability information for each word allowed separation of potentially confounded influences of word length, frequency and predictability on eye movement measures.

2. Methods

2.1. Participants

The participants of the present study were 18 dyslexic and 18 typically reading German-speaking, young male adults who were recruited from two large longitudinal studies on reading development (e.g., Wimmer, Mayringer, & Landerl, 2000). Invitation for participation was based on previous reading assessments and final group assignment was based on a reading assessment 2 years before the current study. Criteria for dyslexia were a performance below percentile 10 on a reading speed test and an estimated IQ higher than 90 (based on four subtests of the Wechsler Adult Intelligence Scale, WAIS-R; German Version: Tewes, 1991). The reading test presented a list of 71 sentences with the instruction to mark each sentence as meaningful or not. Examples are “People with pale skin and blond hair have an enhanced risk of sunburn” and “*A weighing-machine measures the height of a person*”. Measure was the number of correctly marked sentences within 3 min.

It is clear from the top of Table 1 that the dyslexic group processed only about half of the number of sentences compared to the typical readers with the means corresponding to percentiles of 1 and 56, respectively, based on a preliminary norm sample of 300 university students. The group difference reflects slow reading speed of the dyslexic readers, because errors were very infrequent ($M < 1$ both groups). Table 1 also shows the mean scores of the four WAIS-subtests (Vocabulary, Similarities, Object assembly and Block design; mean scale score = 10, $SD = 3$). Obviously, the dyslexic participants exhibited above-average performance on each subtest, but performance was lower compared to typical readers on the two verbal subtests. Participants had normal or corrected to normal vision and were native German-speakers.

Table 1 also shows the performance of the two groups on a number of measures from tasks which were presented together with the eye movement assessment or in previous assessments. Of interest is the absence of a difference between the groups on a visual string processing task which required detecting a pre-defined target among distractors (letters, which were either visually dissimilar or similar, and letter-like but unfamiliar pseudoletters; Hawelka & Wimmer, 2008). In contrast, on Rapid Automatized Naming tests (RAN; 10 lines of five animal pictures with 1 or 3 syllables and 10 lines of five digits) dyslexic readers performed lower than controls.

The bottom section of Table 1 provides measures from primary school assessments. The school entrance assessment – before the beginning of reading instruction – revealed above average scores on a non-verbal IQ test of both the dyslexic and unimpaired readers, but the dyslexics scored lower than controls on a RAN test (eight lines of four object pictures). A

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spelling test administered in Grades 3 or 4 revealed markedly poorer performance of the dyslexic readers compared to the controls.

2.2. Apparatus and procedure

Eye movements were recorded (monocular for the right eye) with an EyeLink 1000 tower mount system (sampling rate: 1000 Hz; SR Research, Ontario, Canada). Participants sat at a viewing distance – held constant by a forehead and a chin rest – of 52 cm to the screen. The nine point calibration routine took about 3 min and was conducted before the presentation of 12 familiarization trials, was repeated after training and at the halftime of the experimental run (i.e., after the presentation of 72 sentences) after which the participants were offered a short break. Criterion for calibration was a tracking error of less than 0.5° of visual angle.

Sentences were presented typed in mono-spaced, bold font (Courier New, 14 pt.) presented on a 21 in. computer screen (1024 × 768 pixel resolution, 120 Hz frame rate). From the fixed viewing distance a single character had a width of 0.3°. Sentence length varied from 5 to 11 words ($M = 7.9$).

Prior to each sentence presentation a fixation point was presented near the middle of the left screen frame (position in pixels: $x = 200$, $y = 384$). After the system had detected a fixation (minimum duration: 100 ms) on the fixation point, sentences were presented in such a way that the first word was centrally fixated. Participants were instructed to silently read the sentence. Looking at an *x* – presented at the bottom left corner of the screen – terminated sentence presentation and triggered the reappearance of the fixation point (or the appearance of a question mark, see below). When the system did not detect a fixation at the fixation point within 5 s the system was re-calibrated.

To assure that participant fully processed the sentences, comprehension questions were orally presented by the experimenter after about every fourth sentence. The questions could mostly be answered by uttering a single word. The verbal response was not crucially hampered by the chin rest and did not influence the quality of the eye movement recordings. Importantly, dyslexic readers had no problems in comprehending the sentences as wrong answers rarely occurred (both groups: $M < 1$).

2.3. Data treatment and analyses

All fixations, which occurred after processing the final word of a sentence, and fixations shorter than 80 or longer than 800 ms were excluded from the analysis (less than 2% for each group). We only analyzed fixations which occurred during the first encounter of the word (i.e., during first pass reading). A total of 45,897 fixations ($N = 31{,}126$ and 14,771 for dyslexic and typical readers, respectively) were entered into the analyses.

The first word of a sentence was not considered for analyses and the few words with more than 9 letters were also omitted. This left still a total of 916 words. For analysis of the length effect, the few 2-letter words were added to 3-letter words so that length ranged from 3 to 9 letters. Word frequency is expressed by the logarithmic values of occurrences per million in the CELEX data base (Baayen, Piepenbrock, & van Rijn, 1993). Word predictability refers to the probability of which an upcoming word can be guessed on the basis of the sentence context and predictability norms were sampled by the Potsdam group (Kliegl et al., 2004) with a norm sample of 272 unimpaired adult readers. The continuous log frequency and predictability values were – in accordance with the seven levels of word lengths – categorized in seven equally sized bins with a minimum of 76 and 34 items per bin for frequency and predictability, respectively.

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3. Results

3.1. Dyslexic eye movement abnormalities

Table 2 shows group differences for several measures which are commonly used to characterize dyslexic eye movement abnormalities. The dyslexic readers exhibited massively increased gaze durations (i.e., the sum of fixation durations during first pass reading) and a doubled number of fixations per word compared to the typical readers. The mean forward saccade length of the dyslexic readers was substantially shorter than that of the typical readers. Importantly, there were no group differences in the percentages of regressions between words which were defined as the relative amount of between-word regressions in the total amount of between-word eye movements. Analogously, the percentages of progressive (i.e., in the reading direction) and regressive within-word eye movement refer to the total amount of within-word eye movements. As evident from Table 2, the dyslexic readers exhibited a substantial higher number of progressive than regressive within-word eye movements. This was less the case for typical readers. However, they exhibited only a very small amount of within-word eye movements. Table 2 further shows that dyslexic readers skipped only very few words and processed a substantial amount of words with multiple fixations. However, there was little difference between the groups in the percentage of singly fixated words. All types of fixations (single fixations, first and successive of multiple fixations) were markedly prolonged by about 50–60 ms for the dyslexic group. However, similar to the typical readers, the dyslexic readers exhibited no difference between the durations of single fixations and of the first of multiple fixations and shorter durations for fixations following first fixations.

3.2. First fixation location

Fig. 1 shows the effect of word length on the first fixation location for the two groups. Our unimpaired readers exhibited a typical pattern with “overshooting” the center of short words (i.e., up to about 5 letters), hitting the center for words with 6 and 7 letters, and “undershooting” longer words. In contrast, the dyslexic readers hit the center of short words only, and massively “undershot” medium and long words. The group difference was reliable from 4-letter words onwards ($ts > 3$).

3.3. Effects of length and frequency

In a next step, we examined group differences in the effects of word length and frequency on number of fixations and gaze duration per word (see Fig. 2). Note that, for the purpose of presentation, the *x*-axis of word frequency was scaled from high to low so that the effects of length and frequency go in the same direction. The main observation from Fig. 2 is that both number of fixations (first section) and gaze duration (second section) of dyslexic readers were much more affected by length and frequency than those of typical readers. Furthermore, for each length and for each frequency level, dyslexic readers exhibited more fixations and longer reading times. This overall difference becomes most evident from the observation that dyslexic reading performance for the shortest (3- and 4-letter) words corresponded roughly to unimpaired performance for the longest (8- and 9-letter) words. The same relationship applies for word frequency with again dyslexic performance for the most frequent words corresponding to unimpaired performance for the most infrequent words.

The final section of Fig. 2 shows the effects of length and frequency for those words which received a single fixation only. Such single fixations are suggestive of lexical route processing via orthographic whole-word recognition, if there is little effect of word length. Indeed, as evident from Fig. 2, there was no systematic increase of fixation duration with length. Actually, both groups exhibited the shortest durations for 6- and 7-letter words and

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increases of fixation duration occurred only for 8- and 9-letter words. Also of interest is the observation that single fixation durations of both groups were not affected by frequency from high to medium and increases were only observed for the two bins of the most infrequent words.

The right section of Fig. 2 shows the results of regression analyses for each of the three dependent measures using linear-mixed effect models (LME; Pinheiro & Bates, 2000). Specifically, we regressed each dependent measure (number of fixations, gaze duration and single fixation duration) on length (fixed factor) and included frequency and predictability as random factors. In a corresponding set of regression analyses, each dependent measure was regressed on frequency with length and predictability as random factors. These analyses allow an estimation of the unique effects of length and frequency. Estimation of these effects was important, because length and frequency were substantially correlated ($r = -.61$) and there were also small correlations of length and frequency with predictability (−.19 and .30, respectively). The error bars in Fig. 2 represent 1 standard error of the fixed effects which were used to test the significance of the fixed effects against 0 by the means of one sample *t*-tests and 17 degrees of freedom ($n - 1$). Group comparisons (two-sided independent sample *t*-tests) were conducted with the fixed effect of each group, the associated standard errors and 34 degrees of freedom ($n - 2$).

For number of fixations, the fixed effects of length differed reliably from zero and the fixed effect of the dyslexic group was reliably higher than that of the control group. For the typical readers, the fixed effects of frequency did not differ reliably from 0. For the dyslexic readers, the fixed effect of frequency was reliably higher than 0 and reliably higher than that of the typical readers. For gaze duration, the fixed effects of both length and frequency in each group were substantial and the effects were larger for the dyslexic group. The main result of the regression analyses for single fixation duration is the absence of a systematic length effect for both the dyslexic and unimpaired readers.

3.4. Length by frequency interaction

For examining dyslexic group differences of the expected length by frequency interaction on number of fixation and gaze duration, the continuous “independent” factors were categorized into two levels of length and three levels of frequency. This quasi-experimental approach was used for easier comparison of the present findings with response time findings from studies which used single word naming of lexical decisions (e.g., Weekes, 1997). Corresponding to the increase of the length effect from 6 letters onwards (see upper section of Fig. 2), we categorized length as short (up to 5 letters) and long (6–9 letters) items. For the more continuous effect of frequency, we distinguished between three levels (i.e., low, medium, high) which were specified by the log frequencies bands shown in Fig. 3. Only 23 words fell into the category of “long” and “high frequency”, but all other cells contained at least 85 words.

For number of fixations (left section of Fig. 3), an LME analysis with length, frequency and group as fixed factors and predictability as random factor found the expected three-way interaction to be reliable, $t = 8.7$, $p < .001$. Separate analyses for each group revealed that the length by frequency interaction was only significant for the dyslexic readers; $t = 9.8$, $p < .001$, but not for the controls; $t < 1$. Fig. 3 shows that dyslexic readers exhibited a much stronger length-related increase of number of fixations for words of medium and low frequency than for word of high frequency, whereas unimpaired readers exhibited similar small increases for all three frequency levels. The abnormality of the length-related increase of fixations for medium and low frequency levels finds further support by reliable length by group interactions for these two frequency levels (*ts* > 8). For high frequency words, the small length-related increases of number of fixations were more or less identical for both dyslexic and unimpaired readers; $t = 1.2$, $p = .12$. However, even for these words, dyslexic readers exhibited more than one fixation for a substantial number of words. This is particularly surprising in the case of the short items. In contrast, the means for the typical readers (below 1) indicate that high frequency words were frequently skipped.

For gaze duration (right section of Fig. 3), the result pattern was similar to that of number of fixations. Again, the three-way interaction between length, frequency and group was reliable; $t = 7.3$, $p < .001$, but here the length by frequency interaction was not only reliable for the dyslexic readers; $t = 8.0$, but also for the unimpaired readers; $t = 4.8$, $p < .001$. However, as evident from the means in Fig. 3, the length by frequency interactions in the two groups were due to quite different sources. Unimpaired readers exhibited absolutely no length-related increase of gaze duration for high and medium frequency words and a small increase (only about 25 ms) for low frequency words. In contrast, dyslexic readers exhibited dramatic length effects for medium (126 ms) and for low (243 ms) frequency words. This abnormality of the length-related increase of gaze duration is supported by the significant length by group interactions for medium and low frequency words; $ts > 7.6$. For high frequency words, this interaction effect was small, but reliable; $t = 2.8$, $p < .01$, where it resulted from the small length-related increase in gaze duration for dyslexic readers (37 ms) and the complete absence of an increase for unimpaired readers. However, the small length-related increase of gaze duration of dyslexic readers for high frequency words should not distract from the difference to controls (of about 130 ms) even for the short, high frequency words.

4. Discussion

Before interpreting the present dyslexic eye movement findings, a summary of these findings may be useful. As context, we note that our adult sample of poor readers exhibited the typical manifestation of dyslexia in a regular orthography (German in the present study). They suffered from slow effortful reading, but not from a reading accuracy problem. However, due to the asymmetric regularity of German (high in the reading, low in the writing direction), their high reading accuracy was accompanied by low (orthographic) writing accuracy which points to an orthographic lexicon deficit. Also of relevance are findings showing (a) that our dyslexic sample exhibited slow performance on Rapid Automatized Naming (RAN) tests even before learning to read, and (b) that they did not exhibit a deficit on purely visual string processing tasks.

4.1. Summary of eye movement findings

1. With respect to number of fixations during reading, our findings with adult dyslexic participants extend findings from previous eye movement studies with dyslexic children in regular orthographies (De Luca, Di Pace, Judica, Spinelli, & Zoccolotti, 1999; Hutzler & Wimmer, 2004; Zoccolotti et al., 1999). In the present task, requiring silent reading of isolated sentences, our dyslexic readers exhibited about twice the number of fixations compared to unimpaired readers. The frequency of word skipping was massively reduced, whereas the frequency of more than one fixation per word was increased. In relation to number of fixations, regressive eye movements between words were rather infrequent and did not differ from controls. The analyses of within-word eye movements revealed that the higher number of fixations per word of the dyslexic readers were primarily due to frequent progressive refixations. Furthermore, the first fixation location of the dyslexic readers was less affected by word length than that of the typical readers and tended to massively “undershoot” the center of longer words (De Luca et al., 2002; MacKeben et al., 2004).

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2. The global eye movement measures (number of fixations and gaze duration) of dyslexic readers were much more affected by word length (number of letters) than those of unimpaired readers and this was also the case for word frequency. A substantial dyslexic abnormality was already evident for the shortest words and for the most frequent words. Specifically, dyslexic reading performance on the shortest (3- and 4-letter) words – in terms of number of fixations and gaze duration – corresponded roughly to unimpaired performance on the longest (8- and 9-letter) words. The same relationship applied to the effect of frequency. Again dyslexic performance on the most frequent words corresponded to unimpaired performance on the most infrequent words.

3. Of main importance is the finding of an abnormally strong length by frequency interaction shown by dyslexic readers for both number of fixations and gaze duration. Specifically, they exhibited a close to normal length effect for high frequency words and clearly abnormal length effects for words of medium and low frequency. Corresponding to their close to absent length effect for high frequency words, again similar to controls, there was no effect of word length on gaze duration for words which received a single fixation only. Actually, both groups exhibited shortest single fixations for 6- and 7-letter words.

4.2. Dual-route interpretation

In the following, we relate the eye movement findings to the dual-route model, because this model has served as a main framework for interpreting word processing difficulties of dyslexic readers (e.g., Castles & Coltheart, 1993; Ziegler et al., 2008). The left panel of Fig. 4 shows the main components of the model and also illustrates how a familiar (i.e., frequent) letter string and an unfamiliar (infrequent) string may be processed by the model. The first component of the model is a visual feature/letter processor which in parallel transforms the visual input from a word into an abstract letter string which is provided simultaneously to both the orthographic word lexicon (lexical route) and to serial grapheme–phoneme coding (sublexical route) for further processing. The familiar letter string is assumed to find a match in the orthographic word lexicon which provides access to the phonological word with its syntactic and semantic features. In contrast, the unfamiliar string is assumed to reach the phonological word entry via serial grapheme–phoneme conversion of the sublexical route. The right panel of Fig. 4 illustrates how the components of the lexical route may correspond to the processing stages of the word identification module of the E-Z Reader model.

In dyslexia research, the dual-route model gave rise to the distinction between surface dyslexia and phonological dyslexia (e.g., Castles & Coltheart, 1993). Surface dyslexia refers to a specific impairment of the lexical route for processing familiar words and phonological dyslexia refers to a specific impairment of the sublexical route which is assumed to be critically involved in reading unfamiliar words. In English-based dyslexia research, the diagnosis of surface dyslexia is mainly based on specific difficulties with accurate reading of irregular words and the diagnosis of phonological dyslexia is based on difficulties with accurate reading of nonwords (Castles & Coltheart, 1993). As noted in Section 1, in orthographies more regular than English, such a diagnostic approach, based on reading errors, is not possible, because there are no proper irregular words and dyslexic readers – at least from about Grade 3 onwards (Wimmer, 1993) – typically do not suffer from a marked accuracy problem even for nonwords. They typically suffer from a massive and persistent reading speed problem which in most cases affects both words and nonwords (e.g., Landerl & Wimmer, 2008). Bergmann and Wimmer attempted to distinguish between surface and phonological dyslexia on the basis of the speed of orthographic and phonological lexical decisions. This attempt also failed, because of a very high correlation between the two speed measures. However, this difficulty to find subjects with specific lexical and sublexical speed impairments does not imply that the dual-route model may not be useful for characterizing the dyslexic reading speed problem in terms of proximal mechanisms.

4.2.1. Orthographic lexicon deficit

In Section 1, we suggested that part of the reading speed problem of dyslexic readers stems from an orthographic lexicon deficit. This implies – in terms of the dual-route model of Fig. 4 – that the output of the visual feature/letter processor (i.e., the abstract letter string) finds no matching entry in the orthographic lexicon with the consequence of continuation of serial sublexical processing. As noted in Section 1, this proposal was backed by a recent study from our group (Bergmann & Wimmer, 2008) which used accuracy of orthographic lexical decisions to diagnose word-specific orthographic lexicon deficits and found these deficits to be accompanied by slowed phonological lexical decisions. One motivation for the present eye movement study was the concern that phonological lexical decision may pose specific problems for dyslexic readers with the consequence that slow latencies may not reflect reading speed problems in natural silent reading situations. This concern did not find support as the present eye movement findings – similar to latencies of phonological lexical decisions – do speak for an important role of the orthographic lexicon deficit for the reading speed problem of dyslexic readers. A first crude indication of an orthographic lexicon deficit affecting reading speed was the observation that dyslexic readers were much more affected by word length than unimpaired readers. This negative effect was present for number of fixations and even more so for gaze duration. From the dual-route perspective, these abnormal effects of word length indicate reliance on serial sublexical processing which has to take place when letter strings find no match in a deficient orthographic lexicon. In E-Z Reader terminology, this would translate into a failure of the familiarity check. Another indication for a deficient lexicon was the observation that dyslexic readers exhibited single fixation on a word or skipping of a word for 67% of the present word items, whereas unimpaired readers did so for 90%. Important support for the interpretation that single fixations reflect orthographic whole-word recognition is provided by the finding that the number of letters of singly fixated words had no reliable effect on the duration of single fixations. Such absence of a word length effect is expected when all the letters are processed in parallel by the visual feature/letter processor of the dual-route model and in parallel activate an orthographic lexicon entry. Obviously, the same argument can be made when a word receives no fixation at all, because in this case one can assume that letter string processing and orthographic word recognition occurred when the eyes (but not attention) were still on the word which preceded the skipped one.

Further support for an orthographic lexicon deficit comes from the finding of an abnormally strong length by frequency interaction on both number of fixations and gaze duration of dyslexic readers. Specifically, dyslexic readers, compared to unimpaired readers, exhibited a much increased length effect for words of medium and low frequency. Only for high frequency words did dyslexic readers exhibit small length effects which were similar to those of the typical readers. These findings suggest that dyslexic readers were able to rely on lexical route processes based on orthographic lexicon entries only for highly familiar words, but not for words of lower frequency. The present finding of a marked length by frequency interaction for dyslexic readers, stands in interesting contrast to the findings of two studies with dyslexic children which found the same large increase of fixations or reading onset time from short to long items for both words and nonwords (De Luca et al., 2002; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003). The similar length effect for words and nonwords – from the dual-route perspective – suggests that processing of the words was completely dependent on serial sublexical processing. The critical difference between the present study, which found a length by frequency interaction for dyslexic readers, and the studies of De Luca et al. and Ziegler et al. which did not find such an interaction, is the age

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of the dyslexic participants. The participants of De Luca et al. and Ziegler et al. were children (mean ages: 13 and 11 years, respectively), whereas the present participants were young adults (mean age: 18 years). Presumably, the present dyslexic readers were advanced compared to the dyslexic children in the mentioned studies in the sense that they were able to rely on the lexical route for a proportion of high frequency words.

The present study did not directly assess a deficit of the orthographic word lexicon in dyslexic readers. However, the present participants are similar to those of Bergmann and Wimmer (2008) who used an orthographic lexical decision task to directly assess such a deficit. Bergmann and Wimmer found their dyslexic readers to exhibit correct distinctions between correct and incorrect homophonic spellings (e.g., YES to *Taxi* and NO to *Taksi*) for only about 60% of the word–pseudohomophone pairs, whereas unimpaired readers did so for 90% of the word–pseudohomophone pairs. Furthermore, there is direct evidence for an orthographic lexicon deficit of the present dyslexic sample from an assessment in primary school (9 years before the present assessment) which included a spelling test. The present dyslexic readers wrote correctly only 56% of dictated words, whereas the present unimpaired readers did so for 92%. This early measure of the size of the orthographic lexicon was highly associated ($r = .83$) with the combined number of skipped or singly fixated words in the present study. This supports the interpretation that single fixation and skipping of words reflects orthographic whole-word recognition.

4.2.2. Impaired speed of the lexical route

A rather direct reflection of impaired efficiency of the lexical route is the prolongation of fixation duration of about 60 ms shown by the dyslexic readers for words which received a single fixation only and for which dyslexic readers, similar to unimpaired readers, did not exhibit a length effect on fixation duration.

There are three potential sources of the speed impairment of the lexical route. One is that the lexical route impairment arises from slow functioning of the visual feature/letter processor of the dual-route model which in the E-Z Reader model may correspond to early visual processing. Further potential sources are slow activation of orthographic lexicon entries, corresponding to the familiarity check, or slow activation of phonological lexicon entries from instantiated orthographic lexicon entries which corresponds to lexical completion (see Fig. 4). A deficit of the visual feature/letter processor is implied by explanatory accounts of dyslexia which assume a low-level visual deficit (Stein & Walsh, 1997) or a visual attentional problem posed by letter string processing (Facoetti et al., 2006; Valdois, Bosse, & Tainturier, 2004). Contrary to these accounts, the present dyslexic readers did not differ from unimpaired readers on a string processing task which required fast detection of the presence of a target among strings of 5 letters or 5 pseudoletters. Actually, as shown in Table 1, our dyslexic readers tended to perform faster than the controls (for details see Hawelka and Wimmer (2008)). Several further studies from our group provided negative evidence for a speed impairment of dyslexic readers on purely visual processing tasks (Hutzler, Kronbichler, Jacobs, & Wimmer, 2006; Kronbichler, Hutzler, & Wimmer, 2002; Wimmer & Mayringer, 2001). Of specific interest are the findings from an eye movement study with dyslexic readers which found an enormous increase of number of fixations for reading of nonwords, but not when the task was to detect the presence of two adjacent identical letters in sequences of consonant strings (Hutzler et al., 2006). An extensive examination of potential eye movement control problems in Italian dyslexic children also arrived at a negative conclusion (De Luca et al., 1999). However, the largely negative evidence from group studies does not preclude that there may be dyslexic cases with a dysfunction of the visual feature/letter processor of the dual-route model (e.g., Ziegler et al., 2008). What we can conclude is that such cases must be quite rare among dyslexic readers who exhibit the characteristic reading speed problem in regular orthographies.

The present study offers little of direct relevance for evaluation of the two other potential sources of the speed impairment of the lexical route (i.e., slow access from letter strings to orthographic lexicon entries and slow access from orthographic to phonological lexicon entries). However, the slow performance of the present dyslexic readers on versions of the Rapid Automatized Naming (RAN) tests of Denckla and Rudel (1976) provides some tentative information. We first note that the processes required by the RAN tests correspond to lexical route processes, because the RAN tests require rapid naming of sequences of pictured objects or digits. In the present versions, we used pictured objects (for the assessment at the beginning of Grade 1) and pictured animals and single digits (at the assessment 3 years before the present one). Similar to orthographic whole-word recognition of the letter strings, the RAN pictures (or digits) must be recognized (i.e., instantiate a stored representations) and, similar to access from orthographic to phonological word representations in lexical reading, RAN requires access from instantiated visual representations to whole-word phonology. Since our dyslexic readers performed similarly to controls on the letter string processing task of Hawelka and Wimmer (2008), it seems unlikely that the poor performance on the RAN tasks is due to slow visual recognition. Furthermore, visual recognition is very simple when single digits have to be recognized. Therefore, the slow performance on the RAN tests speaks for slow access from instantiated visual recognition units to phonological lexicon entries. This interpretation is further supported by the finding that slow RAN performance of dyslexic readers result from prolonged pause times between name articulations, and not from slow articulation of names (Neuhaus, Foorman, Francis, & Carlson, 2001).

For direct comparison between the dyslexic deficit on lexical route processes in reading and RAN performance, we converted the items per minute measure of the digit RAN test into mean processing time per digit and found this measure to be 70 ms prolonged for the dyslexic compared to the unimpaired readers (M = 395 ms and 325 ms, respectively). This prolongation of access to phonology in the digit RAN test is close to the 60 ms prolongation of their single fixation durations in the present silent sentence reading task. Furthermore, the individual mean single fixation durations were reliably associated with the processing time in the digit RAN test, r = .67. However, this support from RAN test for slow access from orthographic to phonological word entries does not necessarily preclude a dyslexic speed deficit in accessing orthographic word entries from letter string information. From the central tendency measures in Table 1 it is obvious, that only about half of the dyslexic sample may have exhibited a serious RAN deficit with scores roughly about 1 standard deviation below the mean of the controls.

4.2.3. Inefficiency of the sublexical route

The present study – different from the eye movement studies with Italian and German dyslexic readers (De Luca et al., 2002; Hutzler & Wimmer, 2004) – did not present nonwords to examine directly inefficient functioning of the sublexical route of the dual-route model. However, consistent with a specific speed impairment of the sublexical route are the prolonged fixations on words which receive more than one fixation. Such multiple fixations can be taken as rough indication of serial sublexical processing (but see below). Compared to unimpaired readers, the first of these multiple fixations were prolonged by more than 60 ms on average and the successive fixations were prolonged by more than 50 ms. The finding of prolonged initial fixation durations compared to shorter successive fixations of multiply fixated words is important, because it speaks against the plausible possibility that the first of multiple fixations are primarily “misplaced” fixations. The reason is that misplacements of fixations due to oculomotor aiming errors are detected early which results in short fixation durations (e.g., O’Regan & Lèvy-Schoen, 1987; Vitu, McConkie, Kerr, & O’Regan, 2001). Thus, the longer initial fixation durations compared to shorter successive fixations reflect frequent failure of orthographic word recognition, and not frequent occurrence of misplaced fixations.

The dual-route model of Fig. 4 offers two plausible interpretations of these prolonged fixation durations. One is slow access from graphemes to phonemes and the other is slow activation of phonological word forms from the sequence of phonemes supplied by grapheme–phoneme conversion. Slow activation of phonemes is suggested by a study from our group which found that dyslexic readers required substantially longer presentation times for reliable report of a cued element of strings of consonant letters (Hawelka, Huber, & Wimmer, 2006). This task requires only activation of phonemes and no further activation of phonological word entries. Similar dyslexic speed deficits were found in a study which measured naming of singly presented letters (Castel, Pech-Georgel, George, & Ziegler, 2008; Jones, Branigan, & Kelly, 2009). This support for slow access from graphemes to phonemes does not rule out that slow access from phonemes (or assembled phonology) to word phonology may not also contribute to the speed impairment of the sublexical route.

A further aspect of inefficiency of sublexical reading may have to do with the grain size of sublexical orthographic and phonological segments (Ziegler & Goswami, 2006). Dyslexic readers may rely on small units such as graphemes and phonemes whereas competent readers may rely on lager orthographic segments such as letter clusters for consonant onsets or rimes. Consistent with this interpretation, Thaler et al. (2009) found that dyslexic children exhibited a specifically increased proportion of fixations on words which contained consonant clusters. A failure to rely on larger sublexical orthographic patterns may contribute to the disproportionately increased number of fixations for low frequency words shown by dyslexic readers in the present study.

We note that inefficient functioning of the sublexical route is expected from the dominant version of the phonological deficit explanation of developmental dyslexia which assumes a specific difficulty of dyslexic readers to access phonological segments below the lexical level (e.g., Snowling, 2000). In English-based dyslexia research, this difficulty is assumed to affect the acquisition of the grapheme–phoneme correspondences (e.g., Rack, Snowling, & Olson, 1992). In more regular orthographies with easy grapheme–phoneme associations, one may expect that a phonological deficit affects the speed with which sublexical phonological segments get activated. One of us introduced “phonological speed dyslexia” to distinguish this version of the phonological deficit account from the standard English-based account (Wimmer, 1993).

4.3. Eye movement control of dyslexic readers

By linking E-Z Reader to the dual-route model of visual word recognition we followed Pollatsek et al. (2006 p.43) who suggested “*using the E-Z Reader model format to examine models of word recognition in the context of reading*”. The assumption of E-Z Reader that word processing is strictly serial (i.e., one word at a time) made the linkage to the dual-route model relatively straightforward. A basic assumption derived from the model was that typical readers have a preferred saccade length of 7 letter spaces which is adjusted – often less than optimal (McConkie et al., 1988) – to target the center of upcoming words. The data from our typical readers were consistent with this assumption as (a) their mean length of forward saccades was about 7 letter spaces and (b) they systematically “overshot” the center of short and “undershot” the center of long words. In Section 1, we advanced two alternative possibilities of how dyslexic readers may deviate from this pattern. One was that dyslexic readers basically prefer the same saccade length and make the same adjustments towards the center of upcoming words. From this we expected frequent within-word regressions towards the word beginnings due to frequent failures of orthographic word recognition. The second alternative was that dyslexic readers may exhibit a tendency to fixate word beginnings which is conducive for serial, sublexical word decoding. Our findings speak for the latter alternative. Dyslexic readers exhibited a reduced length of forward saccades (only 4.4 compared to 7.4 letter spaces for the controls) and exhibited a reduced influence of word length on the location of first fixations. The effect was that their first fixation was at the center for short words only, and at initial letter positions for long words. Also consistent with a tendency to target the beginnings of words is the finding that dyslexic readers exhibited a high percentage of progressive within-word eye movements. The reduced effect of word length on incoming saccades of our adolescent dyslexic readers corresponds to similar findings of studies with Italian and German dyslexic children mentioned in Section 1 (De Luca et al., 2002; MacKeben et al., 2004).

Another expectation was that the slow functioning of the word identification component for the fixated word will result in a reduced rate of word skipping by dyslexic readers. Specifically, we assumed that slow lexical completion (i.e., access to word phonology and meaning) will cause a delay in shifting attention to the upcoming word (see Fig. 4). This prevents identification of the upcoming word before the execution of the saccade can be canceled. In support for this account we found that the skipping rate of dyslexic readers was very low (only 1 out of 10 words compared to 3 out of 10 for controls) and was accompanied by prolonged fixation durations of singly fixated words. The prolonged single fixations point to inefficient lexical access presumably due to slow access from instantiated orthographic word entries to word phonology which corresponds to the second stage of the word identification process in E-Z Reader. Furthermore, in E-Z Reader theorizing programming a saccade and shifting attention to the upcoming word will not be initiated, if the currently fixated word is processed via the sublexical route which is frequently the case for dyslexic readers.

An unexpected finding was that dyslexic readers exhibited more than one fixation even for short words (3–5 letters) of high frequency and at the same time exhibited only a very small increase of number of fixations for long high frequency words which did not differ from controls. A plausible interpretation may be based on the fact that a substantial number of the short high frequency words are articles which differ only in the final letters reflecting different case endings. Examples are *der, dem, den, einer, einem, einen, eines*, etc. One may assume that dyslexic readers relied on orthographic whole-word recognition of these letter strings which sometimes required a second fixation to disambiguate between the case endings. This interpretation suggests that equating orthographic whole-word recognition with single fixations (and word skipping) may somewhat underestimate orthographic whole-word recognition.

In summary, the present data provide a detailed characterization of the reading speed deficit of dyslexic readers in regular orthographies. We found that dyslexic readers for a substantially reduced number of words exhibited efficient visual word processing (i.e., single fixation or skipping). This pattern was interpreted as indicative of a deficient orthographic lexicon. The prolonged durations of single fixations were interpreted as speed impaired access to whole-word phonology. A further indication of inefficient processing was observed when words received more than one fixation. One critical finding was a higher number of fixations (resulting in the abnormal word length effect). This was interpreted as reliance on smaller sublexical orthographic recognition units. Another finding was that multiple fixations were prolonged which may reflect slow access to sublexical phonology. Finally, the linkage of the dual-route model of single word processing with the E-Z Readers model made possible the examination how the inefficient functioning of dual-route components affects the eye movements of dyslexic readers during silent sentence reading.

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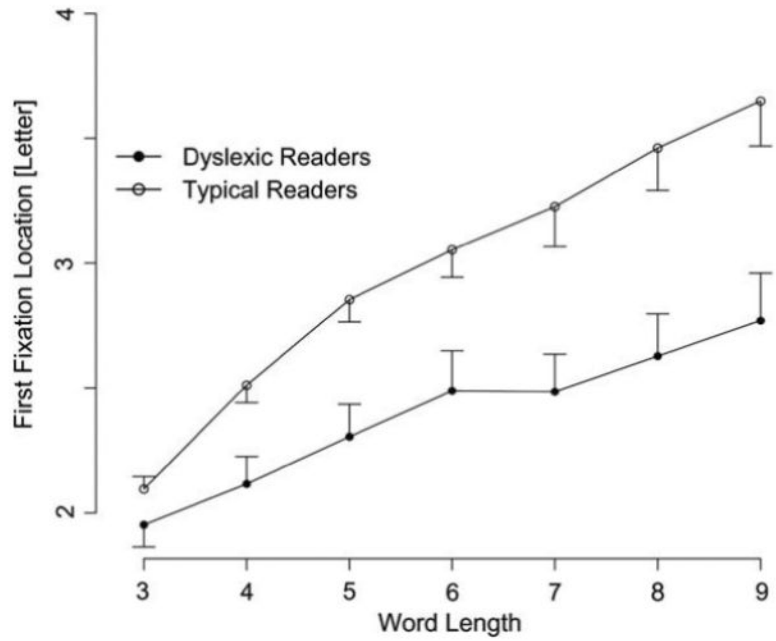

Fig. 1.
The location of the first fixation in relation to word length. Error bars indicate 1 standard error of the mean.

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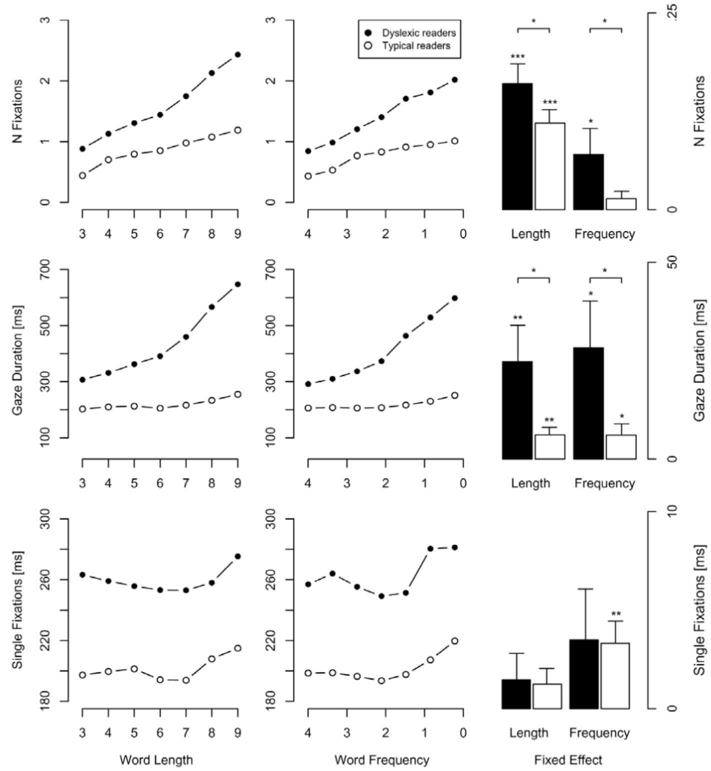

Fig. 2.
The upper section shows how mean number of fixations and gaze durations related to word length and frequency. The lower section shows how word length and frequency affected the fixation duration of singly fixated words. The bar charts represents the linear fixed effects (and 1 standard error) of length and frequency on number of fixations, gaze duration and single fixation duration. Stars above the bars indicate the significance of the fixed effects and stars above brackets indicate the significance of the group differences with *p < .05, **p < .01, and ***p < .001.

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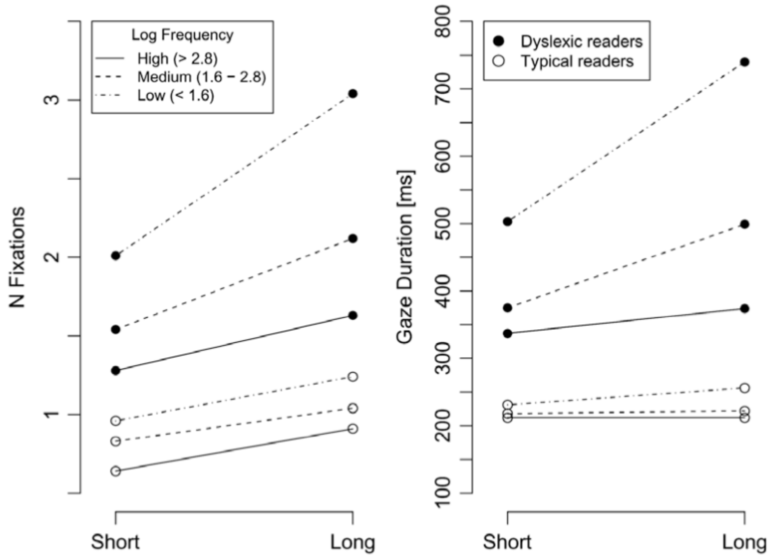

Fig. 3.
Mean number of fixations and gaze duration for short (2–5 letters) and long (6–9 letters) words of high, medium and low frequency.

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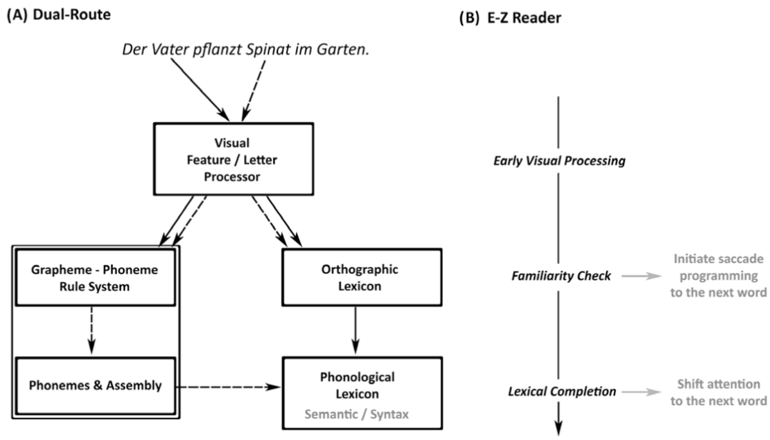

Fig. 4.

The left panel is a schematic illustration of how the dual-route model of visual word processing may process the highly familiar word "Vater" (*father*; log frequency: 3.2) and the less familiar word "Spinat" (*spinach*; log frequency: 1.3). For the former, the model relies on the lexical route and gain access to word phonology via an instantiated orthographic whole-word recognition unit. For the latter, word phonology is assembled via serial grapheme–phoneme conversion. The right panel illustrates how the processes of the word identification system of E-Z Reader (Reichle et al., 2003; Pollatsek et al., 2006) may correspond to the lexical route of the dual-route model. See text for details.

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Table 1

Means (standard deviations) of the dyslexic and typical readers for age, sentence reading, actual cognitive measures, visual string processing and Rapid Automatized Naming (RAN). The bottom section gives cognitive measures from primary school assessments. The final column gives the values of *t*-test group comparisons (*df* = 34 unless denoted otherwise)

	Dyslexic readers	Typical readers	*t*-value
Age (y:m)	17:8 (1:3)	17:6 (1:1)	0.6
Sentence reading	27 (6)	53 (8)	11.1 ***
Cognitive measures (WAIS-subtests)			
Vocabulary (Verbal scale)	11.2 (2.0)	13.6 (2.0)	3.7 **
Similarities (Verbal scale)	11.6 (2.0)	13.1 (1.8)	2.4 *
Block design (Performance scale)	12.1 (2.4)	12.0 (1.5)	0.2
Object assembly (Performance scale)	13.4 (3.0)	11.8 (2.8)	0.6
Visual string processing (ms) [a]			
Low confusable letters	688 (140)	707 (96)	0.5
High confusable letters	777 (153)	822 (115)	1.0
Pseudo-letters	894 (162)	903 (109)	0.2
RAN (items/min)			
Animals (1 syllable)	83 (17)	96 (18)	2.2 *
Animals (3 syllables)	59 (11)	72 (15)	3.0 **
Digits	157 (30)	190 (33)	3.1 **
Previous measures [b]			
Non-verbal IQ	114 (14)	108 (10)	1.3
Object RAN (items/min)	41.2 (7.0)	51.6 (11.3)	3.2 **
Spelling (% correct)	56 (10)	92 (5)	11.0 ***

* $p < .05$.

** $p < .01$.

*** $p < .001$.

[a] See Hawelka and Wimmer (2008) for details.

[b] Data from $n = 17$ and 16 dyslexic and typical readers, respectively ($df = 31$). See Wimmer et al. (2000) for detailed task descriptions.

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Table 2

Means (standard deviations) of global eye movement characteristics, percentages of skipped, singly fixated and multiply fixated words, fixation durations, mean group differences and *t*-values of the group comparisons

	Dyslexic readers	Typical readers	M_{Diff}	$t(34)$
Global measures				
Gaze duration (ms)	406 (151)	215 (27)	191	5.3***
Fixations per word (*N*)[a]	1.9 (0.8)	0.9 (0.2)	1.0	5.3***
Forward saccade length (*N* of letters)	4.4 (0.9)	7.4 (1.3)	−3	7.7***
Between-word regressions (%)[b]	14 (6)	11 (6)	3	1.2
Within-word eye movements (%)[c]				
Forward refixations	71 (10)	58 (19)	13	2.5*
Regressive refixations	29 (10)	42 (19)	−13	2.5*
Fixation probabilities (%)				
Skipped words	12 (1.4)	31 (2.1)	−19	7.5***
Singly fixated words	55 (1.8)	59 (1.4)	−4	1.7
Multiply fixated words	33 (2.3)	10 (1.3)	23	8.5***
Fixation durations (ms)				
Mean fixation duration	247 (43)	190 (14)	57	5.4***
Single fixations	260 (37)	197 (17)	63	6.7***
First of multiple fixations	262 (44)	198 (24)	64	5.5***
Successive fixations	219 (45)	166 (18)	53	4.6***

* $p < .05$.

** $p < .01$.

*** $p < .001$.

[a] *N* of fixations during first pass reading.

[b] Percentage of between-word regressions in the total amount of between-word saccades.

[c] Percentages of regressive and progressive refixations in the total amount of within-word saccades.