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Eye movements in German-speaking children with and without dyslexia when reading aloud

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ABSTRACT.
Purpose: **The phonological difficulty and orthographic regularity of a language influence reading strategies. Only a few studies have been conducted in readers of German, which has a high grapheme–phoneme correspondence. The aim of this study was to investigate, firstly, the influence of different levels of phonological difficulty of reading material in German on reading in children and, secondly, to compare the reading strategies of German children with findings in English-speaking readers.**
Methods: **Eye movements in 16 German children with dyslexia and 16 age-matched control children (mean age 9.5 ± 0.35 years) in the third and fourth grades of school were recorded by scanning laser ophthalmoscope while they read aloud two texts of differing levels of difficulty.**
Results: **In the dyslexia group, reading speed was slowed, and the number of saccades and regressions was raised markedly, although the percentage of regressions only slightly. The number of eye movements increased in both groups with increasing text difficulty, although much more in the dyslexia group than in the control group, whereas fixation duration was not influenced.**
Conclusions: **Phonological difficulty influences reading speed and eye movement pattern: children with dyslexia markedly increase their number of eye movements and analyse the text in smaller units per fixation, but keep fixation duration constant. This strategy reflects their favouring of the indirect, sublexical route of grapheme–phoneme conversion, whereas readers of English-language texts are more likely to prefer the whole-word approach, i.e. the direct, lexical route that is associated with orthographic memory.**

Key words: developmental dyslexia – eye movements – perceptual span – phonological text difficulty – reading – regular orthography – scanning laser ophthalmoscope

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Introduction

Specific dyslexia research dedicated to studies of eye movement has found marked differences in patterns of eye movement between readers with and without dyslexia, mainly in terms of increased numbers of eye movements and prolonged fixation duration (Buswell 1922; Taylor et al. 1960; Rubino & Minden 1973; Adler-Grindberg & Stark 1978; Heller 1979; Eltermann et al. 1980; Pavlidis 1981, 1991; Ciuffreda et al. 1985; McConkie et al. 1991; Olson et al. 1991; Eden et al. 1994; Rayner 1998; De Luca et al. 1999; Hutzler & Wimmer 2004). Some authors have interpreted the pathological patterns as representative of a primary ocular motor control deficit (Pavlidis 1981) and inability to suppress express saccades (Fischer & Weber 1990; Fischer et al. 1993; Biscaldi et al. 1998). Others interpret the erratic eye movements as a consequence of difficulties in decoding words. Language has also been shown to influence eye movement in skilled readers (Rayner & McConkie 1975; Rayner 1978, 1998; Stanley & Smith 1983; Hyönä & Olson 1995; Goswami et al. 1998).

Word length and word frequency influence the number and duration of fixations (Hyönä & Olson 1995). In a previous study, we found a pathological eye movement pattern for reading words, but not for naming pictures (Trauzettel-Klosinski et al. 2002). This indicates the phonological deficit as one of the main causes of dyslexia (Bradley & Bryant 1978; Tallal 1980; Frith 1981; Golden & Zenhausern 1983; Wimmer 1993; Fox 1994; Rumsey et al. 1997; Swan & Goswami 1997; Shaywitz et al. 1998; Schulte-Körne et al. 1999; Warnke 1999; [for a review, see von Suchodoletz 1999]). Many studies have found a phonological deficit by means of behavioural, cognitive measures (Snowling 1980, 1981; Rack et al. 1992; Wimmer 1993; Esser & Schmidt 1994; Wagner et al. 1994), as well as by using brain imaging techniques (Price et al. 1994; Rumsey et al. 1994, 1997; Salmelin et al. 1996; Demp et al. 1997; Shaywitz et al. 1998; Fiez et al. 1999; Georgiewa et al. 1999; Helenius et al. 1999; Temple et al. 2001). The concept is further supported by our recent study using magnetoencephalography (MEG), where we found a latency difference in cortical activation at 235–285 ms in the temporal superior and angular gyri that was present during word reading, but not during picture naming (Trauzettel-Klosinski et al. 2006).

Another aspect of dyslexia research concerns the influence of the orthographic regularity of a language on reading strategy. Most research has been conducted in subjects who read English. English has a much lower grapheme–phoneme correspondence than German or Roman languages (Spache 1963; Wimmer 1993, 1996; Landerl et al. 1997a; Goswami et al. 1998; De Luca et al. 1999; Miles 2000; Landerl 2001; Davis et al. 2007) For example, the vowel 'a' in the words 'garden', 'ball' and 'cat' is pronounced differently in each word, whereas its pronunciation is identical in the corresponding German words 'Garten', 'Ball' and 'Katze'. Although people with dyslexia are found to have a slow reading speed in all languages, their rate of reading errors is lower when reading in a regular orthography (Wimmer 1993, 1996; Wimmer & Goswami 1994; Landerl et al. 1997a; Goswami et al. 1998; Davis et al. 2007). These results have been interpreted as caused by different reading strategies. Whereas German-speaking children may prefer the indirect method of word decoding by sublexical grapheme–phoneme conversion, English-speaking children are more likely to use the route of direct word decoding (see the model by Coltheart et al. 2001). The studies referred to here were based on behavioural cognitive measures. However, only two studies have looked at eye movements in German children while reading texts. One of these involved silent reading (Hutzler & Wimmer 2004) and the other used a very small sample (Heller 1979), and both used groups of older children (aged 14 and 11 years). Our group has carried out single-word reading studies in German (MacKeben et al. 2004) and De Luca et al. (1999) in Italian children, using 13-year-old children and examining eye movements according to word length in both cases.

The purpose of the present study was to examine the eye movements of *younger* German-speaking children while they were reading *texts aloud in order to assess differences between subjects with and without dyslexia*. Younger children were chosen because this age group has not yet learned compensating strategies. Eye movement patterns while reading aloud have not been examined in German-speaking children before (except in one study with a very small sample size [Heller 1979]). Furthermore, we were interested in the influence that different degrees of text difficulty might have on eye movements while reading. Finally, we wanted to find out whether potential differences relative to the well-known results found in English-speaking children can provide evidence for different reading strategies.

Materials and Methods

Subjects

Sixteen children with dyslexia and 16 control subjects participated in the study. Inclusion criteria required all children to have: German as their native language; regular attendance in the third or fourth grades of elementary school; normal intelligence (IQ score of > 85 on the Wechsler Intelligence Scale [Tewes et al. 2001]); right-handedness; no uncorrected visual or auditory deficits, and no history of any neurological or psychiatric disorder except dyslexia.

The mean age of the subjects was 113.7 ± 3.8 months (9.5 ± 0.3 years) in the dyslexia group and 115.5 ± 4.4 months (9.6 ± 0.4 years) in the control group.

Reading and spelling performance were assessed by the following standard German test procedures: the Zürcher Reading Test (Zürcher Lesetest [ZLT]; Grissemann 2000); the Würzburger Silent Reading Test (Würzburger Leise Leseprobe [WLLP]; Küspert & Schneider 1998), and the spelling subtest of the Salzburger Reading and Spelling Test (Salzburger

Table 1. Sample characteristics at baseline.

	Dyslexia group	Control group
n	16	16
Male/female	12/4	10/6
Age		
Months	113.7 (3.8)	115.5 (4.6)
Years	9.5 (0.3)	9.6 (0.4)
IQ (HAWIK-III)		
Total	105.1 (5.4)	111.8 (9.0)
Verbal	111.2 (6.4)	117 (10.6)
Performance	97.4 (7.5)	103.1 (8.7)
Spelling		
SLRT (number of errors)	22.7 (3.8)	4.6 (2.0)
Reading		
WLLP (percentile rank)	5.6 (4.2)	61.5 (18.7)
ZLT (total reading time)	125 (36.1)	37.5 (7.7)

Age and test performance are listed as means and standard deviations. HAWIK-III = Hamburg–Wechsler Intelligenztest für Kinder (Hamburg-Wechsler Intelligence Test for Children) 3rd edition; SLRT = Salzburger Lese-Rechtschreibtest; WLLP = Würzburger Leise Leseprobe; ZLT = Zürcher Lesetest.

Lese- und Rechtschreibtest [SLRT]; Landerl et al. 1997b). The performance of the 16 children with dyslexia was below the 16th percentile and at least 1.5 standard deviations (SD) below the performance expected according to their HAWIK-III (Hamburg–Wechsler Intelligenztest für Kinder [Hamburg–Wechsler Intelligence Test for Children] 3rd Edition) score (Schulte-Körne et al. 2001). All control children achieved at least an average score (Table 1). The Strengths and Difficulties Questionnaire (SDQ) (Goodman 1997) and the DISYPS-KJ (Diagnostik System für Psychische Störungen im Kindes- und Jugendalter [Diagnostic System for Psychiatric Disorders in Children and Adolescents]) (Döpfner 2000) questionnaire concerning hyperkinetic disorders were filled out by both parents and teachers between the first and second sessions in order to substantiate the anamnesis. The characteristics of both groups are shown in Table 1.

Eye movement recording

A scanning laser ophthalmoscope (SLO model 101; Rodenstock GmbH, Munich, Germany) was used to image the retina and the stimuli (in this case, text) simultaneously. This method allows to assess the absolute position of the fovea and of the stimuli simultaneously with high spatial resolution of < 5 arcmin (Fig. 1) and moderate temporal resolution of 20 ms. The video-recording clearly shows how the fovea scans the text (for an example, see http://www.amd-read.net/dyslexia.html). This method does not need time-consuming calibration and reduces the artefacts caused by head movements, provided that the image is not degraded by shadowing caused by suboptimal positioning of the eye relative to the SLO. Each sequence was recorded on videotape (50 video fields/second) with a vertical interval time code. The synchronized sound recording allowed us to assess the subjects while they were reading aloud, which is not usually feasible during eye movement recording. Reading aloud allows for direct control of the reading process and gives information about mistakes and fluency and thus, albeit indirectly, about comprehension. In single-word analysis, the time between the point at which the fovea first lands on a word to the beginning of articulation can be measured very precisely, as we have shown previously (MacKeben et al. 2004).

Reading aloud was also desirable for this study because it is used in standard reading tests for children, such as the SLRT (Landerl et al. 1997b) and the ZLT (Grissemann 2000).

Ophthalmological examination

All children underwent a full ophthalmological examination to rule out the presence of refractive anomalies, heterophorias and heterotropias, hypoaccommodation and sensory deficits or morphological eye diseases.

Stimuli

Two texts from the SLRT (Landerl et al. 1997b) were selected. The SLRT is based on the basic vocabulary corpus of German-speaking primary school pupils and accounts for word frequency (Pregel & Rickheit 1987). The children in our study were asked to read the texts aloud. Text 1 was designed for students in the third and fourth grades (i.e. it corresponded to the elementary school grade of the children being tested). This text was 57 words long and had to be divided into two parts in order to show them in the SLO (Part 1.1 contained 26 words; Part 1.2 contained 31 words). This text contained several difficult composite nouns (e.g. 'Krankenhaus' [hospital], 'Rettungsauto' [ambulance]). The median length of words in the text was 8 letters (range 2–16 letters).

Text 2 was designed for students in the first and second grades (i.e. it was two levels below that of the controls and approximately corresponded to the reading age of the children with dyslexia). It contained 30 short and simple words (median word length 4 letters; range 2–9 letters).

The more difficult Text 1 was always presented first in order not to induce a training effect by starting with the easier Text 2 (which we expected to be easy for the dyslexia group). The texts were shown in the SLO at a text size of two times magnification compared with newspaper print. This size was determined to provide optimal visibility for children in a pilot experiment, and is similar to the print size used in standard reading texts (SLRT, ZLT and WLLP) and in school books used in the third and fourth grades.

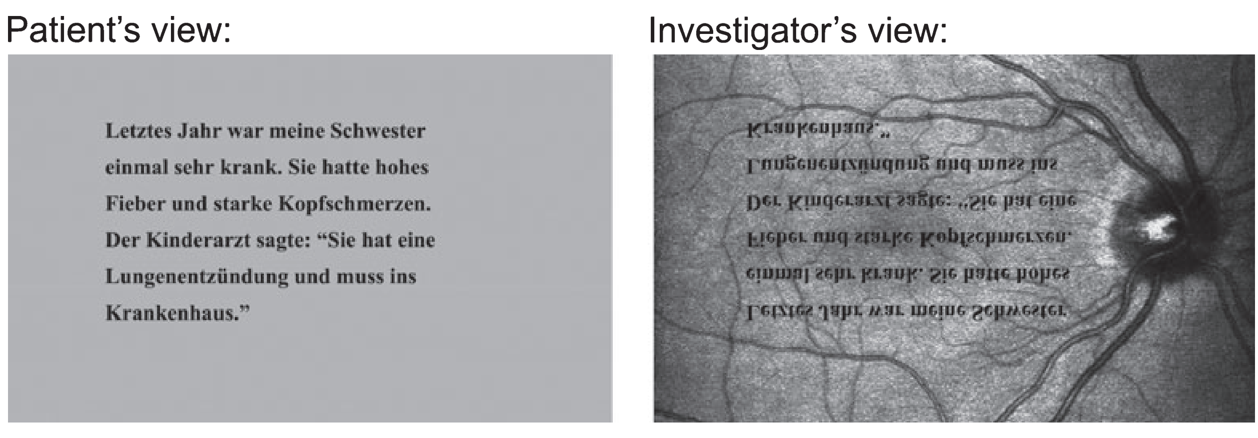

Fig. 1. The text is scanned directly onto the retina using the scanning laser ophthalmoscope (SLO). The subject sees the black text upright on a bright red background; the investigator sees a horizontally mirrored image of the text (Text 1.1) simultaneously with the moving retina. This allows for direct observation of word-by-word foveal fixation (fixation here is on the word 'starke' [third line up]), and, consequently, of how the text is visually scanned during reading (see also video demonstration: http://www.amd-read.net/dyslexia.html).

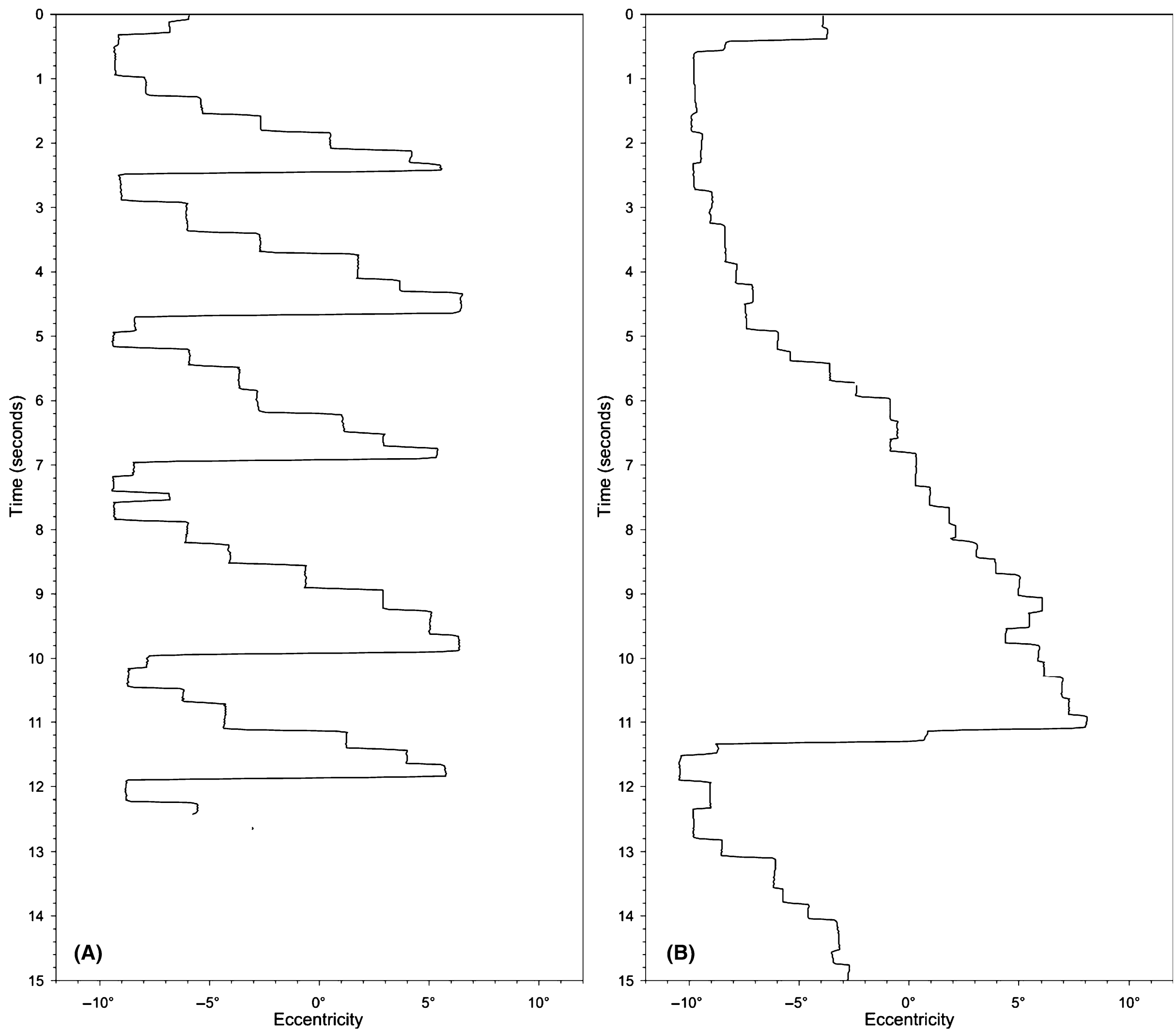

Fig. 2. Eye movements in a child (A) without dyslexia (control) and (B) with dyslexia, while reading Text 1.1. The fovea position is dependent on time (x/t plot). The control child needs approximately 12 seconds to read the six lines. The child with dyslexia reads only the first line during this time and makes many more saccades and fixations, including several regressions.

Procedure

Firstly, a semi-structured telephone interview with the parents was performed to gather information regarding the inclusion and exclusion criteria. Each child was then seen individually in two sessions. The first session included a detailed analysis of the inclusion and exclusion criteria, the ophthalmological examination and the assessment of reading and spelling performance (SLRT, ZLT and WLLP). Two sets of questionnaires were given to the parents at the end of the session and another set was forwarded to the child's teacher. In the second session the intelligence test (HAWIK-III) and the SLO examination were performed.

Before the SLO examination, the children were made familiar with the experiment using a specially prepared handbook, which demonstrated and explained the task and the procedure in a standardized manner. The SLO examination always started with other stimuli so that the children could become accustomed to the device before the texts were presented. The SLO examination was performed monocularly with the dominant eye (determined by having the subject look through a stably mounted kaleidoscope without using the hands).

Data analysis

Horizontal and vertical co-ordinates of the fovea relative to the stimuli (which are necessary to compute the position of the eye during a saccade or fixation period) were calculated for each field (50 fields/second) and each videotape by means of a customized semi-automatic computer program. Subsequently, the co-ordinates were transferred into x/t-plots showing the horizontal fovea position versus time (Fig. 2). The spatial and temporal eye movement parameters of interest were calculated based on these x/t-plots.

Main parameters

Principal parameters included:

(1) reading speed measured in words/minute (words/min), determined from the time between the point at which the fovea landed on the first word to the end of articulation of the last word of a text;

(2) number of forward saccades (called 'saccades' in the following), an eye movement in the reading

direction, which is larger than half an *n*-space (= 0.19 °);
(3) amplitudes of saccades in degrees;
(4) percentage of saccades made against the reading direction (called 'regressions'), and
(5) fixation duration, a holding position ≥ 100 ms.

Minor parameters

Minor parameters included:

(1) the number of regressions (backward saccades [against the reading direction]);
(2) the number of fixations (this parameter results from all saccades and regressions and is used here for comparison with other studies), and
(3) the return sweep, a backward eye movement to the beginning of the next line. Any additional regression during the return sweep was called an 'add-to-return-sweep' (ATRS).

Statistical analysis

We used JMP (Version 4.0; SAS, Inc., Cary, NC, USA) for statistical analysis. Paired *t*-tests were used to test the hypothesis of equal expected values for the mean reading speeds of Text 1 versus Text 2 within one sample (dyslexia or control subjects). To test the same hypothesis between groups (dyslexia versus control subjects), the *t*-test for independent samples was used. The *t*-test was applied based on the normal distribution of reading speeds (Shapiro–Wilk test). The global significance level for the 14 statistical tests was determined by an α of 0.05. To correct for multiple testing, the local significance level was determined for each test with $\alpha = 0.0083$. Because of multiple testing, only the main parameters underwent statistical analysis. The minor parameters were handled only descriptively. We also used two-way repeated-measures analyses of variance (ANOVA) with Group (dyslexia, control) as the between-subject factor and Text (easy, difficult) as the within-subject factor to assess the differences in reading speed and eye movement behaviour.

The research was conducted in accordance with the tenets of the Declaration of Helsinki and was approved by the local ethics committee of the Medical Faculty, University of Tübingen.

Table 2. Eye movement parameters while reading texts of different levels of difficulty (Text 1 for third and fourth grade schoolchildren; Text 2 for first and second grade schoolchildren).

Parameter	Text	Dyslexia group Mean	Dyslexia group SD	Control group Mean	Control group SD	Difference between groups
Main parameters†						
Reading speed, words/min	1	40.56	14.58	119.56	17.60	p < 0.0001
	2	50.88	22.53	136.94	23.49	p < 0.0001
No. of saccades/word	1	3.16	0.90	1.37	0.20	p < 0.0001
	2	2.68	0.90	1.21	0.90	p < 0.0001
Saccade amplitude, degrees						
	1	1.46	0.29	3.02	0.52	p < 0.0001
	2	1.48	0.32	2.74	0.40	p < 0.0001
Character spaces	1	3.83	0.76	7.94	1.36	
	2	3.89	0.84	7.20	1.05	
% regression	1	19.17	5.86	12.93	6.26	p < 0.0073
	2	18.42	9.01	12.25	7.51	p < 0.0033
Fixation duration, ms	1	350	6	250	3	p < 0.0001
	2	350	6	240	3	p < 0.0001
Minor parameters†						
No. of regressions/word	1	0.84	0.41	0.21	0.11	
	2	0.71	0.57	0.16	0.13	
No. of fixations/word	1	4.01	1.24	1.58	0.23	
	2	3.39	1.39	1.38	0.26	
Add-to-return-sweep	1	1.55	0.33	1.00	0.31	
	2	1.54	0.31	1.04	0.36	

† Because of multiple testing, only the main parameters underwent statistical analysis. The minor parameters were handled descriptively.
SD = standard deviation.

Results

Main parameters

The results are summarized in Table 2.

The influence of text difficulty

Eye movement parameters were clearly influenced by the degree of difficulty of the reading material. As expected, the difference in reading speed between the groups was highly significant for both texts ($p < 0.0001$) with factors of 2.9 and 2.7, and both groups showed a significant dependence on text difficulty. Both groups were significantly faster (control group, $p = 0.0006$; dyslexia group, $p = 0.0034$) at reading the easier Text 2 versus the more difficult Text 1. Saccade amplitude was significantly shorter in the dyslexia group while reading both texts ($p < 0.0001$). However, in this respect, text difficulty was seen to influence only the control group (Fig. 3B).

The number of saccades/word was, of course, higher in the dyslexia group, and both groups read the easier text with fewer saccades/word than they did the more difficult text ($p < 0.0001$) (Fig. 3A).

Two-way repeated-measures ANOVAS were performed separately, with reading speed, number of saccades/word and saccade amplitude as dependent variables. The outcomes indicated that the control group read faster, made fewer saccades/word, and exhibited greater saccade amplitudes than did the dyslexia group. The text difficulty also mattered: in the control group, reading speed was faster for the easy text, but the number of saccades/word and saccade amplitude were greater with the difficult text. The dyslexia group showed a bigger difference between the easy and difficult texts than controls in the number of saccades/word (0.52 versus 0.16, respectively), whereas the controls demonstrated a bigger difference between the easy and difficult texts in saccade amplitude than the dyslexia group (0.74 versus − 0.06, respectively). The main effects of group and text were significant for all three dependent variables entered, whereas group × text interactions were significant only for the number of saccades/

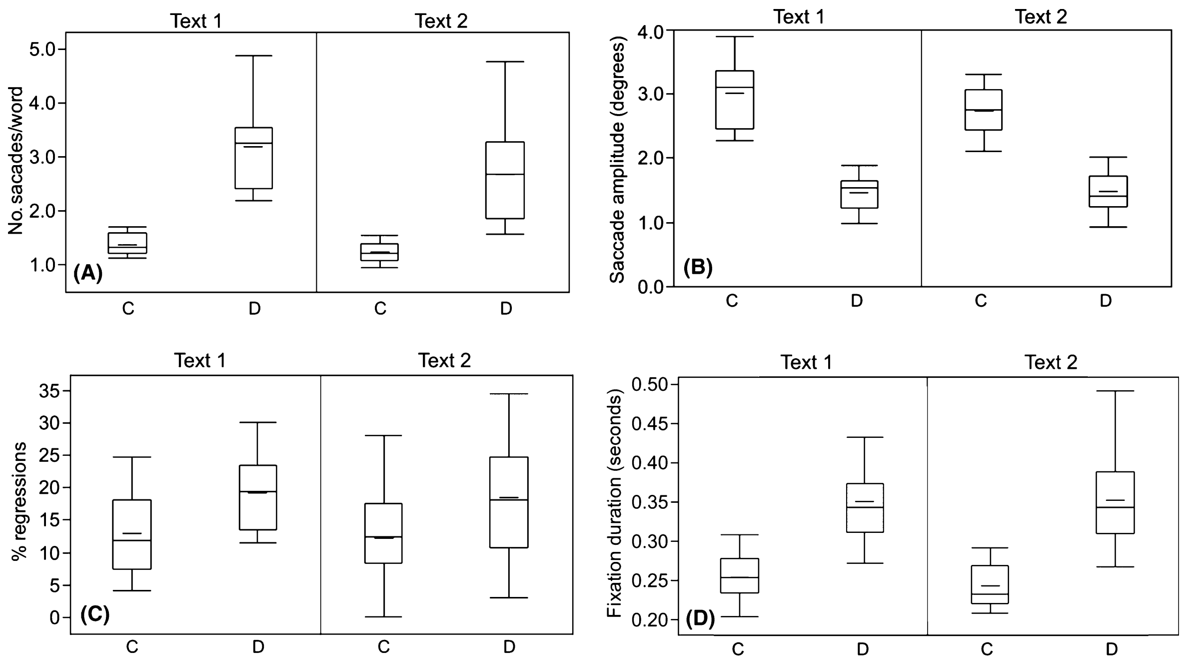

Fig. 3. Boxplots of eye movement parameters. (A) The number of saccades/word is increased in the dyslexia group. Both groups show fewer saccades/word when reading the easier Text 2. (B) Saccade amplitudes are higher in the control than in the dyslexia group. There is little difference in amplitude between Texts 1 and 2. (C) The percentage of regressions is moderately increased in the dyslexia compared with the control group, and slightly less for Text 2. (D) Fixation duration is prolonged in the dyslexia group, but text difficulty makes no difference in either group. C = control group; D = dyslexia group.

word and saccade amplitude (reading speed: main effect of group, $F_{1,30}$ = 1105.825, $p < 0.0001$, main effect of text, $F_{1,30}$ = 31.114, $p < 0.0001$; number of saccades/word: main effect of group, $F_{1,30}$ = 368.276, $p < 0.0001$, main effect of text, $F_{1,30}$ = 16.897, $p < 0.0001$, group × text interaction, $F_{1,30}$ = 5.652, $p < 0.025$; saccade amplitude: main effect of group, $F_{1,30}$ = 1518.914, $p < 0.0001$, main effect of text, $F_{1,30}$ = 12.847, $p < 0.001$, group × text interaction, $F_{1,30}$ = 16.183, $p < 0.0001$).

The percentage of regressions in the total number of eye movements was also higher in the dyslexia than the control group (Text 1: p = 0.0073; Text 2: p = 0.0033 [i.e. below the required significance level of 0.0083]) (Fig. 3D).

The mean fixation durations for Text 1 and Text 2 were significantly higher ($p < 0.0001$) in the dyslexia group compared with the control group, but there was no difference between Texts 1 and 2.

Minor parameters

The absolute number of regressions/word for both texts was much higher in the dyslexia than the control group. Because of the increased number of saccades and regressions, the number of fixations was increased in the dyslexia group. The number of additional regressions during return sweeps (ATRSs) (Table 2) was not dependent on text difficulty, but differed between the groups.

Discussion

This study aimed to analyse eye movement patterns during reading in a regular orthography in young children, with and without dyslexia, who have not yet developed adaptive strategies. The reading material consisted of two standard texts of differing levels of difficulty in order to assess the influence of phonological difficulty.

Few studies of eye movement in dyslexia during text reading have been performed in German-speaking children (Heller 1979; Hutzler & Wimmer 2004), whereas several have been performed in English-speaking children (Buswell 1922; Taylor et al. 1960; Griffin et al. 1974; Adler-Grindberg & Stark 1978; Eltermann et al. 1980; O'Regan 1980; Pavlidis 1981, 1991; Olson et al. 1983, 1991; Ciuffreda et al. 1985; McConkie et al. 1991; Eden et al. 1994; Rayner 1998; Starr & Rayner 2001). As far as other languages with regular orthographies are concerned, only one study of eye movement in dyslexia subjects using Italian has been carried out (De Luca et al. 1999); however, this used single-word reading, whereas all other studies used behavioural measures.

In comparison with previous work on regular orthography, the current study shows three important differences: we examined younger children (mean age 9.5 years); we asked our subjects to read texts aloud (in order to obtain direct control and to make our tests compatible with the standard test situation; see Materials and Methods), and we used two standardized texts of different levels of difficulty. Because of these three aspects, our data are not directly comparable with those of other study designs. Direct comparisons between studies are limited by variable text difficulty and differences in study design (e.g. single-word or text-based reading; whether the reading mode is silent or aloud; the degree of orthographic regularity of the language).

The degree of orthographic consistency in a language has an effect on phonological decoding, which is important for the acquisition of reading skills. Therefore, it is of interest to study the differences between languages. English is less consistent than German. Several authors have reported that German-speaking children read more slowly but more accurately than English-speaking children, who tend to read faster but show a higher rate of mistakes (Wimmer 1993; Landerl et al. 1997a; Frith et al. 1998). However, if studies have used standardized texts that are appropriate for the age of the cohort, a rough comparison can be performed despite these limitations.

One of the studies that is most comparable with ours, in that it used a regular orthography and German texts, is that of Hutzler & Wimmer (2004). However, the children studied by these authors were older and they read silently (Hutzler & Wimmer 2004).

We will first compare outcomes in our dyslexia and control groups for each parameter, and will then discuss the findings of other studies using regular orthographies. Finally, we will consider comparisons with studies in English-speaking readers that match at least one of our experimental conditions (reading aloud, similar age or influence of phonological difficulty).

Reading speed

In the present study, our control children showed reading speeds of 120 words/min for Text 1 and 137 words/min for the easier Text 2. The dyslexia group read Text 1 at a speed of 41 words/min and Text 2 at a speed of 51 words/min (Table 2), making them 2.9 and 2.7 times slower, respectively, than the controls. These speeds are markedly slower than the mean reading speed of low-vision patients, who read at 72 (± 35, SD) words/min after adaptation of low-vision aids (Nguyen et al. 2008).

De Luca et al. (1999) reported that the reading speed of Italian children with dyslexia was reduced by a factor of 2–6 (single-word reading aloud).

Daane et al. (2005) reported a reading aloud speed of 119 words/min in normal English-speaking students in fourth grade, which corresponds with our results.

In addition, reading speed in normal subjects depends on several parameters, such as age, skill, the difficulty of the text and whether the text is read silently or aloud. Most eye movement studies have used silent reading in adult English readers. In studies in English-speaking children, for instance, reading speed for silent reading was 135–164 words/min in normal students and 105 words/min in children with dyslexia (Adler-Grindberg & Stark 1978; Carver 1990).

Eye movements

Number of saccades

The number of saccades/word was increased in the dyslexia group (3.16) compared with the control group (1.37), which is similar (3.0 versus 1.8, respectively) to findings in our previous study with single-word reading, where higher age (mean 13 years) was partly compensated by more difficult words (MacKeben et al. 2004). However, these values are higher than those of De Luca et al. (1999), who analysed single-word reading aloud in Italian readers (dyslexia group 2.18 saccades/word; control group 0.97 saccades/word). The difference between our findings and those of De Luca et al. (1999) cannot simply be explained by differences in word length between the languages because we also found an increase in the number of saccades with the easier Text 2 (which used shorter words). Previous studies showed that the number of saccades correlated highly with word length (Hutzler & Wimmer 2004; MacKeben et al. 2004). However, in a study conducted in parallel with the present research (with the same cohort), we examined single-word reading and found an effect not only of word length, but also of word frequency, as well as a highly significant interaction between word length and frequency. The difference between our findings and those of De Luca et al. (1999) can also be explained in part by the fact that our children were younger (9.5 years versus 13 years). It also indicates the preference of German children for grapheme–phoneme analysis (see 'Number of fixations per word' below), a practice that is less useful to readers using the Italian language, which includes many short and open syllables that can easily be assembled as phonemes and can be analysed in larger units of syllables or morphemes (Burani et al. 2002, 2008; Hutzler & Wimmer 2004).

Hyönä & Olson (1995) showed that normal English-speaking readers perform a higher number of saccades when they are asked to read text material that is above their reading level.

Saccade amplitude

Saccade amplitudes in the present study were 3.02 ° (7.94 character spaces) in the control group and 1.46 ° (3.38 character spaces) in the dyslexia group for Text 1 (Table 2).

The slightly larger saccade amplitude in the control group for Text 1 compared with Text 2 may reflect the higher number of long words in Text 1. As MacKeben et al. (2004) have shown, children without dyslexia are able to adapt their saccade amplitude to word length in a linear manner, whereas children with dyslexia showed this adaptive strategy for short words, but less for longer words, which is reflected by the similarities in their amplitude for both texts in the present study.

The saccade amplitudes for Text 1 in the current study correspond quite well with the values recorded by De Luca et al. (1999) in Italian-speaking children (1.2 ° in the dyslexia group and 2.7 ° in the control group).

Compared with findings by Olson et al. (1991) (6.34 versus 5.36 characters in the control and dyslexia groups, respectively), in whose study children were also asked to read aloud, but were older (14 years), our values are larger in the control group, but much smaller in the dyslexia group. As our texts comprised a much higher proportion of short words, this difference is remarkable and may indicate differences in reading strategies: German dyslexia subjects use the sublexical indirect route for phonological decoding and process only a smaller part of the word during a single fixation. It must be remembered that during fixation of a letter with the fovea, neighbouring letters are perceived. An area of 2 ° to the right and left of fixation is required for fluent reading. This 'minimum reading visual field' (Aulhorn 1953) or 'visual span' (Legge et al. 1997) can be increased in the direction of reading by parafoveal information processing in skilled readers (McConkie & Rayner 1975; Inhoff & Rayner 1986; Trauzettel-Klosinski et al. 1994; Trauzettel-Klosinski & Brendler 1998). This total 'perceptual span' is asymmetric to the right and can cover up to 5 ° or 15 letters in the reading direction. The decreased saccade amplitudes found in dyslexia subjects in the present and our former study (MacKeben et al. 2004) indicate a reduced perceptual span. Similarly, a French study using texts that were read aloud found a decreased visual attention span (Prado et al. 2007).

Percentage of regressions

The percentage of regressions in our study was only slightly increased in the dyslexia group (19.2%) compared with the control group (12.9%) and was found to be normal in the same cohort during single-word reading. Likewise, Hutzler & Wimmer (2004) did not find a difference in the percentage of regressions in German-speaking children with and without dyslexia (19% in both groups) and De Luca et al. (1999) found the percentage of regressions to be equivalent in Italian-speaking children with and without dyslexia.

By contrast, most authors have reported a higher percentage of regressions (19–36%) in English-speaking readers, even in normal primary-school children (McConkie et al. 1991; Olson et al. 1991; Rayner 1998), and an increased rate in dyslexia subjects (Eltermann et al. 1980; Pavlidis 1981; Eden et al. 1994). Only Pavlidis (1981) described lower rates of 12% in a control group but 35% in readers with dyslexia. This difference to the English readers can be explained by the high degree of regularity in grapheme–phoneme correspondence in German and Italian compared with English. This high degree of regularity supports the sequential analysis of the word and allows the German-speaking dyslexia subjects to use the indirect sublexical route, grapheme–phoneme analysis, for word processing, whereas English-speaking children might prefer the direct lexical whole-word route. The fact that the percentage of regressions was slightly increased in the present study, which used full texts, seems to reflect the occasional necessity for the reader to reassure him or herself of the meaning of a word by making a regression while reading continuous text, a need that is irrelevant when reading single words. Additionally, second paths may become necessary at the end of the sentence because of wrong decisions or ambiguous meaning earlier in the sentence.

Fixation duration

Fixation duration was prolonged and did not appear to depend on text difficulty in the dyslexia group (i.e. when the text was more difficult, our dyslexia children used more eye movements rather than increasing their fixation duration). If we compare the results of text reading in German-language studies (including different age groups), it becomes evident from our data that, with increasing age, fixation duration decreases in normal subjects, but not at all or only slightly in dyslexia subjects. This explains the differences between findings in the present study in 9.5-year-old children and those in our former study in 13-year-olds (MacKeben et al. 2004), as well as the results of Hutzler & Wimmer (2004), who found very similar durations of fixation in their dyslexia subjects (367 ms versus our 350 ms), but much faster durations in their control subjects (192 ms versus our 250 ms).

In normal English-speaking readers, fixation duration is reported to be 200–262 ms (range of mean values from several studies) in adults (Carpenter & Just 1981; McConkie & Zola 1984; Ciuffreda et al. 1985; Radach 1994), and 255–292 ms in third and fourth grade schoolchildren (Buswell 1922; Taylor et al. 1960; McConkie et al. 1991; Olson et al. 1991). The latter finding is similar to that in our controls, although the English-speaking readers were older. However, it is interesting that their fixation duration increased in line with increasing difficulty of the text (Rayner & Pollatsek 1989). Although fixation duration might be influenced by the manner of reading (silently or aloud), the fact that fixation durations in our dyslexia subjects did not show dependency on text difficulty, by contrast with those in normal English-speaking readers, may tentatively indicate that English-language readers use a strategy of direct decoding by employing longer fixation rather than increasing the number of eye movements.

Number of fixations per word

In line with the increased number of saccades and regressions, the number of fixations/word is also increased in dyslexia subjects (Table 2). The children in our study showed a much higher number of fixations compared with those in the study by Hutzler & Wimmer (2004) (which also used German-speaking children) in both the control (1.58 versus 0.83 fixations/word) and dyslexia (4.01 versus 1.53 fixations/word) groups, which can be largely explained by the lower age of our children (9.5 versus 14 years). The fact that our children read aloud, whereas those in Hutzler & Wimmer (2004) read silently, may have a minor influence, primarily because reading aloud adds articulation time to word retrieval time. In a previous study, using picture naming, we found articulation time to be much less influential, but some dyslexia subjects may have additional articulation disorders (Heilmann et al. 1996; Fawcett & Nicolson 2002). The effect of age is in good agreement with findings from a study in normal children by Lefton et al. (1978), who reported that, during age-appropriate progress in reading ability, fixation duration and number of regressions decrease and saccade amplitude increases.

Interestingly, the number of fixations/word in our control children was also higher than that found in studies in normal English-speaking children of the same age (1.58 versus 1.3 fixations/word) (Adler-Grindberg & Stark 1978; Ciuffreda et al. 1985; McConkie et al. 1991), which may tentatively indicate the different strategy of German-speaking children, who often move through the word in small steps and use a grapheme–phoneme conversion strategy. The higher number of fixations cannot be attributed to the SLO method because the lower temporal resolution of the SLO would be more likely to miss some eye movements than to increase them. Furthermore, previous studies did not show major differences between the results of different eye tracking methods as long as the same definitions for the eye movement parameters were used (Trauzettel-Klosinski et al. 1994; Teschner et al. 1995).

Both our research and that performed by Hyönä & Olson (1995) used material borrowed from standardized tests, namely, the SLRT (Landerl et al. 1997b) in the German-speaking population and the Spache Diagnostic Reading Scales (Spache 1963) in the American population. The word frequency in the texts is based on the basic vocabulary corpora for corresponding school ages (Carroll et al. 1971 [for American children]; Pregel & Rickheit 1987 [for German children]). Hyönä & Olson (1995) focused on the effects of word length and word frequency on fixation patterns in children with and without dyslexia. We report word length and word frequency effects in German children during single-word reading in a parallel paper (Dürrwächter et al.; manuscript under review), whereas, in the present work, we were primarily interested in the effects of text difficulty on eye movement behaviour. In Hyönä & Olson (1995), the average number of fixations/word across the two texts used was 2.0 (see their Table 3, p. 1434), whereas in our study it was 3.2 for the grade-equivalent Text 1. Moreover, Hyönä & Olson (1995) computed their average for short (5–6 letters), medium-length (7–8 letters) and long words (9–11 letters), which were represented evenly (34.6%, 35.8% and 29.6%, respectively), and found that longer words attracted many more fixations. By contrast, the texts used in our study comprised a high proportion of short words (word lengths: 69%, 16.7% and 14.3%, respectively); however, the average number of fixations was greater in German than in American children with dyslexia. This provides additional support for our conclusion that German-speaking children with dyslexia make more fixations/word than do English-speaking children with dyslexia. As the American children with dyslexia in Hyönä & Olson (1995) were on average 5 years older than our German group, age may play an additional role.

Additional regressions during the return sweep (add-to-return-sweep, ATRS)

In normal subjects, a substantial additional regression to the beginning of the next line has been described previously (Gray 1917; Schmidt 1917; Adler 1976; Pavlidis 1981; Stark et al. 1991). An increased number of these additional regressions during the return sweep can indicate marked difficulties in understanding the text (Stark et al. 1991) or a search strategy typically found in patients with left homonymous hemianopia (Gassel & Williams 1963; Meienberg et al. 1981; Trauzettel-Klosinski & Brendler 1998). In the present study, the dyslexia group had an increased number of ATRSs compared with the control group, which may reflect their uncertainty about text comprehension. It cannot be attributed to an oculomotor deficit because we previously found ATRS data to be in the normal range in children with dyslexia during a picture-naming task, where the pictures were presented in a manner similar to the way text is presented (grouped and in several lines) (Trauzettel-Klosinski et al. 2002).

Text difficulty

We had expected that Text 2, which is designed for children in the first and second grades (i.e. two levels below the school age of our cohort), might correspond to the reading age of our dyslexia group and that they might perform much better when reading Text 2. Indeed, they performed better on the easier Text 2 compared with Text 1 in terms of reading speed, and number of saccades and regressions. There was no difference regarding saccade amplitude, percentage of regressions, ATRS and fixation duration. However, Text 2 was still markedly above their reading level, probably because our sample consisted of children with very severe dyslexia (see inclusion criteria and Table 1). This shows that increasing the level of text difficulty primarily increases the number of eye movements, which allows the child to analyse the words in smaller units.

The dyslexia group exhibited a greater difference between the easy and difficult texts than the control group in terms of the number of saccades/word, whereas the controls demonstrated a greater difference between the easy and difficult texts in saccade amplitude. This shows that, with increasing text difficulty, German-speaking children with dyslexia respond with more saccades, whereas their normal peers respond with greater saccade amplitudes in order to adjust to text difficulty, especially to a higher proportion of long words. This behaviour was also observed in our previous study using single-word reading with words of variable length (MacKeben et al. 2004), showing the differences in adjustment of forward-saccade amplitude to word length in normal readers compared with readers with dyslexia.

Conclusions

We found the following significant differences between readers with and without dyslexia:

In the dyslexia group, reading speed was reduced, the number of fixations was increased, and the percentage of regressions was slightly higher. This was more pronounced with the more difficult Text 1. The control group also showed the effect of text difficulty, but less prominently. Fixation duration was higher in the dyslexia group, independently of text difficulty.

Phonological difficulty plays a role in reading speed and number of eye movements, but not in fixation duration. This reflects the strategy used by children with dyslexia, whereby they analyse the text in smaller units, but do not increase fixation duration in line with increasing difficulty of text.

The present work shares a number of findings with those of English-language studies. Reading speed is slowed and the number of saccades and regressions is increased in dyslexia.

Differences were found for the following parameters:

(1) The percentage of regressions was only slightly increased in our dyslexia group when reading full texts and can be normal in single-word reading (Dürrwächter et al.; manuscript under review).
(2) The number of fixations/word was higher than in English-speaking readers, even in our control children.
(3) German-speaking children with dyslexia increase the number of eye movements as the text increases in difficulty, whereas English-speaking children with dyslexia seem to choose longer fixation duration.
(4) Saccade amplitude is smaller in German-speaking children with dyslexia because they process the words in smaller units/fixation.

(5) The number of additional saccades during the return sweep was increased; this parameter was not assessed in other studies.

We suggest that items 1–4 reflect different reading strategies: German-speaking children favour the indirect, sublexical route of grapheme–phoneme conversion, whereas English-speaking children prefer to use the direct, lexical route, the whole-word approach, which is associated with orthographic memory.

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