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Eye-Movements of Dyslexic Children Reading in Regular Orthography: Exploring Word Frequency and Length Effects

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Abstract

Eye-movements represent a great interest in studying the specificity of the reading difficulties that individuals with developmental dyslexia have. In the present study dyslexic children were pair-matched with control children in a sentence reading task. The children read sentences in Bulgarian – a Cyrillic alphabet language with regular orthography. Target nouns with controlled frequency and length were embedded in the sentences. Eye movements revealed highly significant group differences in the gaze time and the total fixation times, word frequency and word length effects as well as interaction for both frequency and length with the group factor. These results, especially the frequency effect found in the dyslexic children, are discussed in the context of previous studies.

Keywords: development dyslexia; eye movements; reading.

Introduction

Developmental dyslexia is described as a condition found in children as young as 6-7 years that impairs their reading skills, while their IQ, reasoning and communication abilities are intact. Still, there is large variability in both the symptoms that dyslexic children demonstrate and in the experimental findings that give support to several theories explaining the underlying causes for dyslexia (see Vellutino, Fletcher, Snowling & Scanlon, 2004 for a review).

Usually, dyslexic children are given non-verbal, phonological or single word reading tasks, which aim to distinguish between different theories. While the rationale behind these experiments is very sound, classical reading experiments are also of great interest. For many years eye movements during reading provide insight into psycholinguistic research. During reading, dyslexic readers exhibit more and longer fixations and a higher percentage of regressions than normal readers. It is still a matter of debate, whether these divergent eye movement patterns of dyslexic readers reflect an underlying problem in word processing or whether they are – as the proponents of the oculomotor deficit hypothesis claim (e.g. Pavlidis, 1981) – associated with deficient visual performance that is causal for dyslexia.

It is a well-documented (and undisputed fact) that eye movements of dyslexic readers differ from those of normal readers. During reading, dyslexic readers exhibit more and longer fixations, shorter saccades and a higher percentage of regressions than normal readers (for review, see Rayner, 1998).

Hutzler, Kronbichler, Jacobs and Wimmer (2006) used a string processing task that imposes the same requirements as reading to visual perception (letter identification) and oculomotor control (moving the eyes in the same pattern as during reading). The task is different from reading as it does not require linguistic or language processing of the visual information beyond letter identification. In the study above the authors found no differences between the eye-movements of dyslexic and normal readers and concluded that differences in eye-movements during reading are not the cause for the impaired performance.

Hyona & Olson (1995) also tested the hypothesis that the specificity of eye-movements of dyslexic readers is the cause for their reading difficulties. They found word length and word frequency effects on eye-movement characteristics of dyslexic readers. The conclusion they made was that the eye-movement patterns of dyslexic readers are affected by the properties of the linguistic material encountered during reading and therefore eye-movement patterns of dyslexic readers are reflection of the difficulties these readers have during linguistic processing (and not vice versa).

Still, there are few studies of text- or sentence-level reading with dyslexic children. An eye-movement study on reading German text passage found word length effects for both dyslexic and normal readers as well as interaction between the groups (Hutzler & Wimmer, 2004). The words taken from the text passage, however, could not be controlled for possibly confounding factors like predictability and frequency. In a similar task of reading short text passages in Italian, De Luca, Di Pace, Judica, Spinelli and Zoccolotti (1999) found once again strong length effects but much smaller frequency main effect that was marginally significant and did not interact with the group factor. Finally, Hyona & Olson (1995) compared a group of dyslexic children with younger ones and found highly significant word frequency and word length effects for both groups in a somewhat similar task – reading aloud of English texts. Although there was no main effect of the group factor, an interaction between length and group was still observed (but only in the subject means).

These experiments show an interesting pattern of results. Dyslexic children seem to show strong length effects and weaker frequency effects in text reading but the differences between normal readers and the dyslexic ones resembles the difference between experienced and average readers or in the children case – of younger, less trained in reading children (Olson, Conners, & Rack, 1991). School practices show that children diagnosed with Dyslexia tend to resent reading and as a result of their reading difficulties, they are less exposed to written text than normal children. Whatever the underlying reason for the various symptoms may be, it is clear that reading practice plays some important role in the later reading behavior of dyslexic children and adults. Indeed most theories predict the length effects which can be explained by difficulties in grapheme-phoneme decoding, oculomotor control, attention. The word frequency effect, however, is closely related to reading experience. It could be argued, that for languages with irregular orthography the grapheme-phoneme decoding could be more problematic for less frequent words than for languages with regular orthography – an explanation suggested by De Luca et al. (1999) for their results that showed much stronger length effects than frequency effects for Italian dyslexic readers when compared to the Hyona & Olson study (1995) on English readers (English is a language with irregular orthography, while Italian – with regular).

Clearly, a further investigation of word frequency and word length effect in reading is necessary in order to explore these inconclusive results.

Experiment

This experiment aims to study word length and word frequency effects in Bulgarian language (a Cyrillic language with regular orthography). Target nouns were embedded in sentences that were controlled for the preceding context (neutral) among other possibly confounding factors, thus providing much more reliable results than words selected from text passages.

Stimuli and design

Before conducting the study there was a preparatory phase. As a first step, we collected a large corpus of children texts in Bulgarian. The corpus contains children books, fairy tales, etc. representative for the age groups studied. It consists of 931 320 words in total, among them 58 605 unique.

From this corpus we selected *short* (5 letters) and *long* (8 letters) concrete nouns (animals, objects, flowers, etc.) that were either *high*- or *low-frequency*. To calculate word frequencies we first computed the raw frequency (number of occurrences per million words) and then we performed a logarithmic transformation. After this we chose 16 short words (5 letters) and 16 long words (8 letters) that have similar low frequency. We also chose 16 short words (5 letters) and 16 long words (8 letters) that have similar high frequency. Summary of the frequencies of the words chosen is presented in Table 1.

Table 1: Summary of the words used in the study. Frequency was assessed as normalized number of occurrences in a 1 million words corpus of texts that are usually read by children (fairy tales, novels, etc.).

		Frequency per million (ln)		
		min	Max	average
5-letter words	low frequency	0	2.26	1.27
	high frequency	3.29	4.6	3.85
8-letter words	low frequency	0	2.01	1.32
	high frequency	2.96	5.97	3.9

In this way, we were able to vary both word length and frequency in a 2x2 design with factors: word length (short vs. long words) and word frequency (high vs. low frequency).

Each of the 64 target words were embedded in a sentence with neutral preceding context. The target word was never the first word in the sentence. The sentences were with content appropriate for children. Example sentences are as follows (the target words are in bold):

- 5-letters, high-frequency: 'Подробна **карта** на океаните е нужна на всеки пират'. (A detailed **map** of the oceans is a necessity for every pirate).
- 5-letters, low-frequency: 'Добрият **бобър** живееше край омагьосаната река'. (The good **beaver** lived near the enchanted river).
- 8-letters, high-frequency: 'Хитрото **чудовище** пресрещаше пътниците и им задаваше гатанки'. (The clever **monster** stopped passengers and gave them riddles).
- 8-letters, low-frequency: 'Червеният **карамфил** беше във високата ваза на земята'. (The red **carnation** was in the tall vase on the ground).

The sentences were counterbalance in two lists, so that each participant saw 32 sentences (8 sentences from each condition).

Procedure and apparatus

Sentences appeared one by one on a screen and were read silently. The task of the children was to read each sentence and to understand it. After reading the sentence, the participant had to press the space bar on a standard computer keyboard. The sentence stayed on the screen until the space bar was pressed and then it disappeared. In order to assure careful reading, control questions appeared after some of the sentences (the questions were related to the content of the sentence). The questions required a ‘yes’ or ‘no’ answer. After reading the question, the participant had to press one of two keys on the keyboard marked with labels ‘YES’ and ‘NO’. There was a fixation cross between the sentences and the participants were instructed to look at it when it appeared.

Each participant had to read 32 sentences, which were presented in a pseudo-randomized order. In the beginning there were 8 practice trials. Data from the practice trials were not included in the analysis. The practice trials were intended to provide an opportunity for the participants to get used to the task.

Eye-movement data were recorded with a Tobii 1750 remote eye-tracker and ClearView 2.7.1 software. The eye-tracker looks like a computer screen with in-built cameras and sensors. That allowed for comfortable and completely unobtrusive recording of eye-movements. Each participant was seated at a distance of approximately 55 cm from the screen. The sentences were presented in black letters on white background. The sentences were presented in Tahoma font (a sans-serif typeface). The size of the letters was chosen to space 3 letters per degree of visual angle. The screen was an integrated 17’ TFT monitor set to its native resolution (1280 x 1024).

The equipment recorded gaze coordinates on the screen every 20 ms. ClearView algorithms were used to compute fixation duration and location from these raw data (the fixation analysis filter was set to 40 pixels fixation radius and 100ms minimal fixation duration). ClearView was also used to control stimulus presentation and to collect participants’ answers.

Participants

Seven dyslexic children and seven children with normal reading skills were matched (in pairs) on age and nonverbal IQ. Full matching data are presented in Table 2. Children with attention disorders were excluded from the sample. All participants had normal or corrected to normal vision.

Data analysis and results

Participants performed well on the control questions – all reported participants had above 80% correct answers (see Table 2 for individual scores).

One of the items (8-letters, high-frequency word) was excluded from the analyses due to typo in the stimulus material.

First-pass durations (gaze duration) and total times were selected as dependent measures that reflect well both word frequency and length effects in reading (Rayner, 1998). **First-pass duration** is calculated as the sum of all fixation durations beginning with the first fixation in a region (the target word) until the reader’s gaze leaves the region, left or right. **Total time** is calculated as the sum of all fixation durations in a region (the target word), regardless of their order.

The eye-movement data were analyzed using two separate analyses of variance (ANOVA): using subjects (F1) and items (F2) as cases.

Table 2: Participants in the study. Each dyslexic child is matched with the child in the row below. The column IQ represents the raw score on a non-verbal Raven test with 36 questions (a point is granted per correct answer). The column “Correct Answers” gives the percentage of correct answers for the comprehension questions during the reading task.

Group	Age (months)	Gender	IQ (raw score)	Correct Answers (%)
Dyslexia	103	Male	29	95
Norm	106	Female	33	100
Dyslexia	120	Male	33	90
Norm	120	Male	32	95
Dyslexia	123	Female	32	100
Norm	125	Female	35	100
Dyslexia	128	Male	32	100
Norm	128	Male	32	100
Dyslexia	130	Male	33	90
Norm	131	Male	35	100
Dyslexia	136	Female	34	95
Norm	142	Female	30	85
Dyslexia	141	Female	20	80
Norm	144	Female	27	90

First-pass duration

First-pass durations (Table 3) were analyzed as a function of word length, word frequency, and group (dyslexic or normal readers).

Comparison between dyslexia group and control group

The subjects analysis (repeated-measures ANOVA) on first-pass duration was performed with two within-subjects factors: word length (short and long) and word frequency (low and high), and group (dyslexic or normal readers) as a between-subject factor. The item analysis on first-pass duration was performed with word length and word frequency as between-item factors, and group as within-item factor.

The main effect of group (dyslexic vs. normal readers) on first-pass duration is significant: $F1(1, 12) = 20.28$, $p \leq 0.001$; $F2(1, 59) = 150.9$, $p < 0.001$. In general, dyslexic readers showed much longer first-pass durations (means were 2044 ms for the dyslexic readers vs. 467 ms for the normal readers).

Table 3: Mean first-pass duration (in ms) as a function of word length and word frequency in dyslexia and control groups.

	Word length	Word frequency high	low	M
Dyslexia group	short	1418	2068	1743
	long	2072	2620	2346
	M	1745	2344	2044
Control group	short	405	421	413
	long	441	600	520
	M	423	511	467

The main effect of word length (short vs. long) on the first-pass duration was significant in the items analysis ($F2(1, 59) = 6.02$, $p < 0.05$) and marginally significant in the subjects analysis ($F1(1, 12) = 4.44$, $p = 0.057$). Longer (8-letters) words lead to longer first-pass durations compared to the short (5-letter) words. Length by group interaction did not reach statistical significance ($F1(1, 12) = 2.16$, $p = 0.17$; $F2(1, 59) = 2.65$, $p = 0.11$). Long words (8-letters) received longer first-pass durations both in the dyslexia and in the control group (see Figure 1).

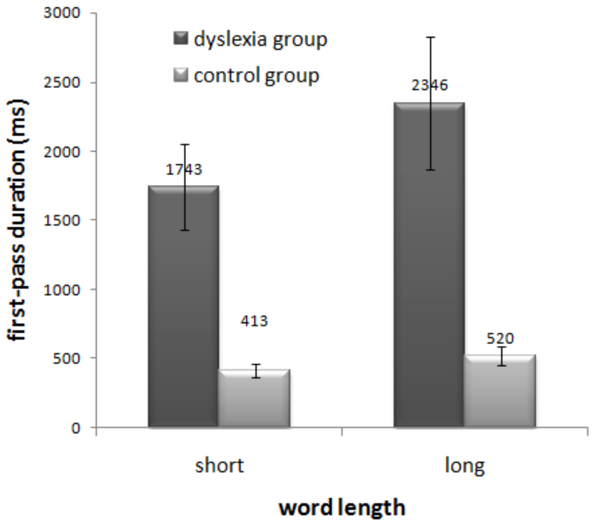

Figure 1: Average first-pass duration (in ms) as a function of word length in dyslexia and control groups. Error bars represent standard error of the mean.

The main effect of word frequency (high vs. low) on first-pass duration was significant in the subjects analysis and in the items analysis: $F1(1, 12) = 10.1$, $p < 0.01$; $F2 (1, 59) = 8$, $p < 0.01$. Low-frequency words lead to longer first-pass durations compared with the high-frequency words. Frequency by group interaction was also statistically significant in both subjects and item analysis: $F1(1, 12) = 5.6$, $p < 0.05$; $F2(1, 59) = 5.86$, $p < 0.05$ (see Figure 2). Additional tests on simple effects in items analysis reveal that word frequency effect is significant in dyslexia group ($p < 0.05$) and not significant in the control group ($p = 0.13$). The interaction reflects the fact that low frequency words (compared to high-frequency words) lead to greater increase in first-pass duration only in the dyslexia group.

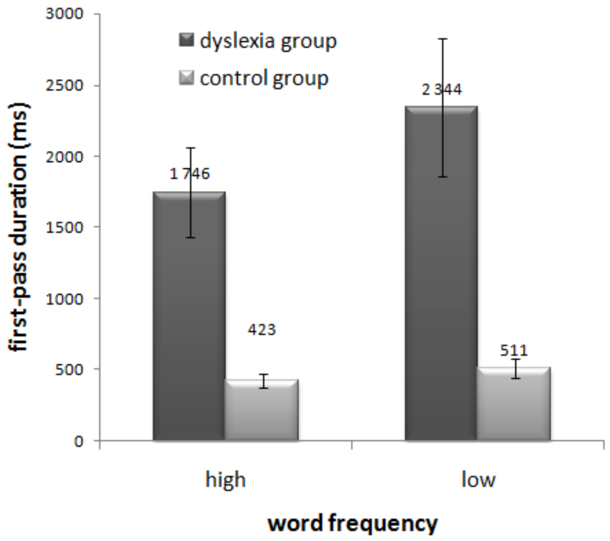

Figure 2: Average first-pass duration (in ms) as a function of word frequency in dyslexia and control groups. Error bars represent standard error of the mean.

Summary of the results for first-pass duration The comparison between dyslexia group and control group demonstrates that *dyslexic children have much longer first-pass duration* in general. Their first-pass durations are approximately 4-5 times longer than for the control group. There was also main effect of word frequency. However, the frequency by group interaction and the additional analysis revealed that the increase in first-pass duration for low-frequency words is present only for the dyslexic group. Main effect of word length on first-pass duration is also found: long words receive longer first-pass durations both in the dyslexia and in the control groups.

Dyslexic children show longer first-pass durations for the long words compared to the short words (word length effect) and for low-frequency words compared to high-frequency words (word frequency effect). So, it seems that eye-movements of dyslexic children are affected by such lexical factors as word length and word frequency.

First-pass durations for dyslexic readers seem to be affected to a greater extend by word-frequency, unlike in some of the previous studies.

Total time

Total times (see Table 4 for means) were analyzed as a function of word length, word frequency, and group (dyslexic or normal readers).

Table 4. Mean total time duration (in ms) as a function of word length and word frequency in dyslexia and control groups.

	Word length	Word frequency		
		High	low	M
Dyslexia group	short	1928	2783	2355
	long	3063	3671	2346
	M	2495	3227	2861
Control group	short	545	556	551
	long	620	747	683
	M	583	652	617

Comparison between dyslexia group and control group The subjects ANOVA on total time was performed with two within-subjects factors: word length (short and long) and word frequency (low and high), and group (dyslexic or normal readers) as a between-subject factor. The item analysis on total time was performed with word length and word frequency as between-item factors, and group as within-item factor.

The main effect of group (dyslexic vs. normal readers) is significant in the subjects and in the items analysis: $F1(1, 12) = 28.4$, $p < 0.001$; $F2(1, 59) = 154.3$, $p < 0.001$. In general dyslexic readers showed longer total time gaze durations compared to the normal readers (means are 2861 ms for the dyslexic readers vs. 617 ms for the normal readers).

The main effect of length on total time was significant in both subjects analysis and items analysis ($F1(1, 12) = 5.52$, $p < 0.05$; $F2(1, 59) = 6.66$, $p < 0.05$). Longer words (8-letters) led to longer total time gaze durations compared to the shorter (5-letters) words. Length by group interaction did not reach statistical significance in both analyses ($F1(1, 12) = 3.25$, $p = 0.096$; $F2(1, 59) = 3.31$, $p = 0.074$). Additional tests on simple effects reveal that word length effect is significant in dyslexia group ($p < 0.05$) and in the control group ($p < 0.01$). Reading for long words had longer total time durations both in the dyslexia and in the control group (see Figure 3).

The main effect of frequency was significant in both analyses: $F1(1, 12) = 6.47$, $p < 0.05$; $F2 (1, 59) = 6.68$, $p < 0.05$. Low-frequency words led to longer total time durations compared with the high-frequency words. Frequency by group interaction was statistically significant in the items analysis ($F2(1, 59) = 5.71$, $p < 0.05$) and marginally significant in the subjects analysis ($F1(1, 12) = 4.44$, $p = 0.057$) The interaction between word frequency and group is presented in Figure 4. Additional tests on simple effects revealed that word frequency effect is significant in the dyslexia group ($p < 0.05$) and not significant in the control group ($p = 0.43$). The interaction reflects the fact that low frequency words lead to greater increase in total time duration only in the dyslexia group.

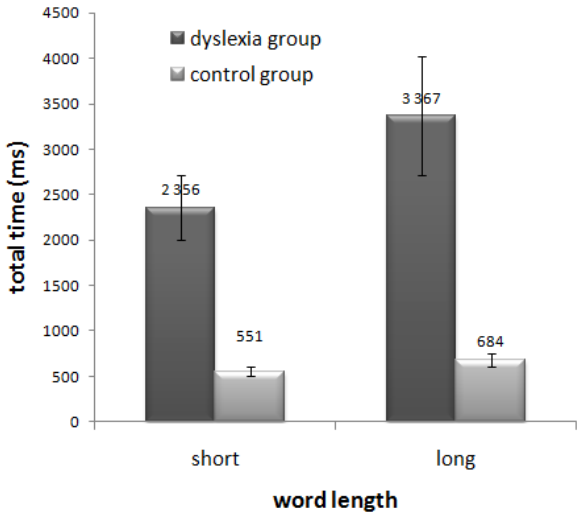

Figure 3: Average total time duration (in ms) as a function of word length in dyslexia and control groups. Error bars represent standard error of the mean.

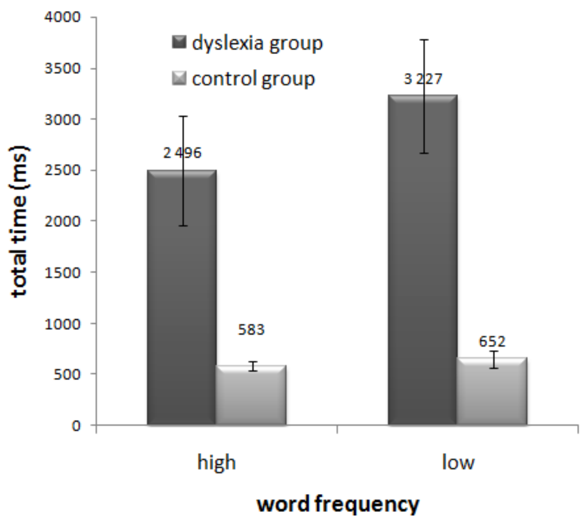

Figure 4: Mean total time (in ms) as a function of word frequency in dyslexia and control groups. Error bars represent standard error of the mean.

Summary of the results for total time The comparison between dyslexia and control groups showed that dyslexic children had generally longer total time for viewing the target words than the controls. There was main effect of frequency. However, the frequency by group interaction and the additional analysis revealed that the increase in total time for low-frequency words is present only for the dyslexic group. Long words receive longer total time durations both in the dyslexia and in the control groups.

The dyslexic children show word length and word frequency effects in eye-movements.

General Discussion

The overall gaze duration and total time for the target words were much longer than the reported by Hutzler & Wimmer (2004) and Hyona & Olson (1995). This could be explained by the age of the dyslexic children – in this study they were between second and fourth grade, while in the above-mentioned studies, the dyslexic children were about 7th grade (about 14 years old). As many dyslexic children tend to develop different strategies with age which help them overcome their reading problems, thus we reason that studying eye-movements of younger dyslexic children give us the possibility to study the specificity of the their reading difficulties without the confounding effect of such strategies.

Another possible explanation for the results lies in the silent reading for comprehension task. The children were highly motivated to reply accurately, which can be seen by the very high number of correct answers (see Table 2). We argue that this task is more natural than reading aloud, which sometimes can be done without any comprehension.

Using sentences with embedded target words allowed better controlling for confounding factors and successfully varying word length and word frequency as independent factors.

The main effect of word length replicated most of the previous findings. The interaction between length and group (well-established in previous research) failed to reach significance probably due to the small number of participants. Word frequency, however, showed somewhat different pattern than former studies. Word frequency effects were very weak for Italian dyslexic readers (De Luca et al. 1999) and did not interact with the group factor in neither De Luca at al. (1999), nor Hyona & Olson (1995). This discrepancy once again can be explained by both the age of the participants and the task - the later, however, seems more probable, since frequency effects reflect not only lexical access but also some comprehension and integration processes that take important part in reading for comprehension unlike reading aloud for example. These results contradict previous findings that claim there is no frequency effects in dyslexic children in regular orthography, or that these effects are much weaker than the length effects. The explanation that is suggested is that the frequency effects stem from the irregular orthography. Our data show that this is not the case and that frequency effects are well manifested in the dyslexic population even in a language with regular orthography.

Conclusion

The results from the current study show that young dyslexic children have extremely slow, but otherwise normal reading patterns that are governed not only by word length but also by frequency – an effect that usually marks good reading skills. The interaction between frequency and group implies that there is some higher-level processing impairment that inhibits the recognition of rare words or that the children simply do not have the same vocabulary range as the controls.

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