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Global reading processes in children with high risk of dyslexia: a scanpath analysis

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Abstract
The study presents the first systematic comparison of the global reading processes via scanpath analysis in Russian-speaking children with and without reading difficulties. First, we compared basic eye-movement characteristics in reading sentences in two groups of children in grades 1 to 5 ($N=72$ in high risk of developmental dyslexia group and $N=72$ in the control group). Next, using the scanpath method, we investigated which global reading processes these children adopt to read the entire sentence and how these processes differ between the groups. Finally, we were interested in the timeframe of the change in the global reading processes from the 1st to the 5th grades for both groups. We found that the main difference in word-level measures between groups was the reading speed reflected in fixation durations. However, the examination of the five identified global reading processes revealed qualitative similarities in reading patterns between groups. Children in the control group progressed quickly and by the 4th grade engaged in an adult-like fluent reading process. The high-risk group started with the beginner reading process, then similar to first graders in the control group, engaged mostly in the intermediate and upper-intermediate reading processes in 2nd to 4th grades. They reach the advanced process in the 5th grade, the same pattern preferred by the control group second graders. Overall, the scanpath analysis reveals that although there are quantitative differences in the word-level eye-tracking measures between groups, qualitatively children in the high-risk group read on par with typically developing peers but with a 3-year reading delay.

Keywords Children · Developmental dyslexia · Eye-tracking · Reading · Russian · Scanpaths

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Introduction

Over the last few decades, eye-tracking has been proved to be a productive methodology in examining reading abilities in children (and adults) with reading impairments, such as developmental dyslexia (DD). Although there is still no consensus on the theoretical underpinnings for the DD (e.g., the phonological theory (Snowling, 2000; Stanovich, 1988) vs. the magnocellular theory (Stein, 2001)), the experimental studies that use the conventional eye-movement measures to investigate reading produce quite comparable results (see overview below). These measures (fixation durations and count, skipping, and regression probabilities) provide information about quantitative characteristics of eye movements per each word in a sentence or a text. Much less, however, is known about whether reading skills of children with and without DD differ on a global qualitative level, i.e., whether children with DD read the entire sentences (or texts) using qualitatively similar to typically developing children eye-movement patterns. Furthermore, it is not clear whether these reading patterns in children with reading difficulties change the same way as in typically developing children when they become older and have more experience with reading materials.

The current study fills the gap by presenting the first systematic comparison of eye-movement sequences — scanpaths — in reading the entire sentences between two groups of Russian-speaking children in grades 1 through 5: typically developing children (control group) and children with the high risk of developmental dyslexia. We start with a brief overview of what is already known about eye-movement behavior via conventional measures in children with DD. We then discuss the scanpath approach as the tool to investigate global qualitative differences in reading patterns between two groups and end the introduction section with the specific research questions in this study.

Conventional eye-movement measures: children with dyslexia vs. typically developing children

The study by Lefton et al. (1979) was one of the earliest to investigate eye-movement differences between English-speaking children with reading difficulties and typically developing children. In reading paragraphs of texts, 11-year-old children that were classified as poor readers produced longer fixation durations (418 ms) and more regressions in text (41.1) than good readers (307 ms and 25.5 regressions, respectively). Since then, many more recent studies confirmed the findings by reporting longer fixations, more regressions, and shorter rightward saccades for the readers with dyslexia (Barrington, 2019 for review, Biscaldi et al., 1998; De Luca et al., 2002; Hatzidaki et al., 2010; Janita & Kapoula, 2011; Hawelka & Wimmer, 2005, Prado et al., 2007). Several other studies also found that readers with dyslexia tend to skip words less frequently and reread the words more times compared to typically developing peers (De Luca et al., 1999, 2002; Hawelka et al., 2010; Hutzler & Wimmer, 2004).

Notably, the differences in these eye movements seem to disappear if the readers are matched not on the basis of age but on the basis of the reading fluency (Hyönä & Olson, 1995; Rayner, 1985a, b, 1998). Rayner (1998) suggests that the observed eye-movement differences are in fact the consequences of the delays in reading skill development stemming from the deficit in linguistic processing of the material (cf. Hutzler et al., 2006). In general, the results in the studies that matched participants according to their reading ability as opposed to matching by age indicate that children with dyslexia produce eye movements that are similar to typically developing children who are 2–3 grades older than them (see Barrington, 2019 for review).

Despite showing quantitative differences in basic eye-movement measures with age-matched controls, children with DD still show sensitivity to word length and word frequency in reading (Kliegl et al., 2004), the effects that are regularly reported in studies with typically developing children (Blythe & Joseph, 2011). In particular, children with DD produce longer fixation durations, more saccades, and fewer skips in longer and less frequent words (Hatzidaki et al., 2010; Hawelka et al., 2010; Hyönä & Olson, 1995; De Luca et al., 1999; MacKeben et al., 2004; Ziegler et al., 2003). Notably, the word length effect appears to be more pronounced in the languages with shallow orthography, in which there is a consistent mapping between graphemes and phonemes with few irregularities (De Luca et al., 1999; MacKeben et al., 2004). For instance, De Luca et al. (1999) found that when reading in Italian, children with DD made one additional fixation every time the word increased by 2 letters, whereas for the control group, the additional fixation was made for every 5-letter increase in the word length. The authors suggest that these effects primarily stem from the reading strategies that children with DD adopt when reading in shallow orthographies such as German, Italian, or Spanish (see Suárez-Coalla & Cuetos, 2012; Trauzettel-Klosinski et al., 2010 for similar conclusions). The children tend to process the material in a serial sublexical manner (as opposed to parallel processing in deep orthographies such as English) causing longer fixations and multiple refixations within the word and, consequently, generally slower reading speed — arguably the main characteristic of developmental dyslexia in shallow orthographies (Carioti et al., 2021; Kirkby et al., 2008).

There are very few available studies that examined basic eye-movement measures in reading in Cyrillic in Russian-speaking children with dyslexia. In general, the findings are consistent with the results of other studies in alphabetical languages. Kornev et al. (2019) asked children with and without dyslexia of younger (9–11 years old) and older (12–13 years old) ages to silently read texts of various genres and difficulty. The authors report significant differences by group in the majority of the standard measures. Compared to the age-matched control group, children with dyslexia in younger group produced more and longer fixations (400 ms vs. 262 ms), more rightward saccades (4 vs. 2 saccades per word), and more regressions (3 vs. 0.8 regressions per word) with shorter amplitude. In older groups, the trend continued, except that children now in both groups made the same number of regressions per word (approximately 1). Similarly, Alexeeva et al. (2020) when examining the advantage of LexiaD font on reading in 9–12-year-old children with and without dyslexia found that the former group was much slower in all fixation duration measures (except First Fixation Duration in one of the fonts). The authors also confirmed the effects of word length and word frequency for both groups in reading in Russian, but the children with dyslexia were more sensitive to the word length (in Total Time reading) and to word frequency (in Gaze Duration and Total Time reading).

Global reading processes via scanpath analysis: a new perspective

While we know now substantial amount of information about the basic eye-movement measures in reading both in typically developing children (Blythe & Joseph, 2011) and children with dyslexia (see Barrington, 2019; Kirkby et al., 2008 for reviews), there are still very few studies that focus on and compare the global reading patterns of these young readers. In contrast to the conventional “local” measures of fixation durations, skipping, and regression probabilities per word, the global reading patterns draw a fuller picture of eye-movement reading behavior. Specifically, these reading patterns constitute the eye-movement sequences — or scanpaths — that span across the entire sentence or text and "combine" all the conventional eye-movement characteristics. Recently, von der Malsburg and Vasishth (2011) devised a new tool that allows researchers not only to plot readers' eye-movement scanpaths across the entire stimulus but also to compare each individual scanpath of a reader to all other scanpaths of the other participants reading the same sentence. Thus, the scanpath approach can provide valuable information about differences and similarities in global reading patterns among various groups of readers beyond just the word-based quantitative measures.

The scanpath itself constitutes the sequence of chronologically aligned eye fixations that a child (or any individual) produces when reading a sentence. When plotted, scanpath represents a line that connects eye fixations according to their durations, time of occurrence, and x- and y-coordinates on the screen. Fig. 1 presents an example of a scanpath across a sentence that consists of 8 words. We can see that a child reads from left to right, starting with the 1st word in a sentence, she then skips the 3rd word (flat line across 2 words), and

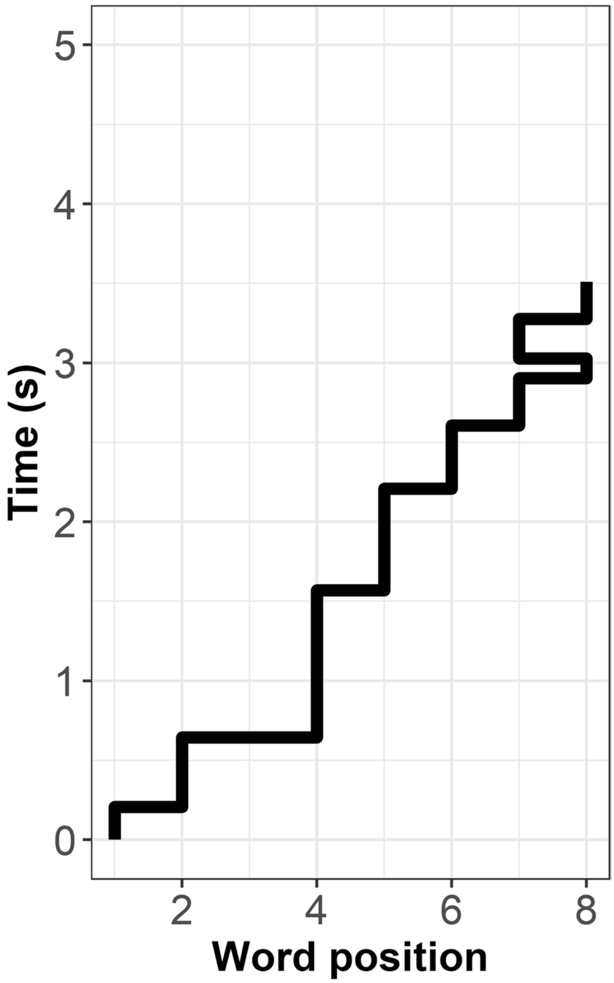

Fig. 1 A scanpath from a sentence reading task: the reader produces skips, long fixations on the word, and short regressions to refixate the word after the eyes moved rightward

fixates the 4th word for a longer time (line is extended vertically). She also rereads the 7th word and finishes reading the sentence at 3.5 s.

In a recent study, Parshina et al., (2021) used the scanpath analysis to identify prototypical reading patterns, or scanpath reading processes, in groups of monolingual Russian-speaking adults and children and compared them to bilingual English-speaking adults learning how to read in Russian. By means of cluster analysis that categorized all scanpaths based on similar reading characteristics, the authors identified three such reading processes among groups. Adult native Russian speakers mostly adopted the fluent reading process characterized by fast reading speed (i.e., short [290 ms per word] and few fixations), many instances of skipping (17% of words in the sentence), and very few regressions (13%). Bilinguals with low reading fluency in Russian engaged in the beginner reading process which included long fixation durations, almost no skipping (6%), and high probability of rereading words (38%) and entire sentences multiple times. Finally, 8-year-old Russian-speaking children without reading impairments preferred the intermediate reading process. This process can be characterized as somewhat in-between the first two: The children read with much slower speed (690 ms per word) than adult speakers of Russian, they produced more short leftward saccades to reread the previous words (25%), skipped words more than bilinguals (9%), and generally avoided rereading the whole sentence. Parshina and colleagues concluded that the intermediate reading process reflects the presence of the "local" difficulties in word recognition stemming from developing grapheme-to-phoneme conversion process (see Parshina et al., 2021 for similar findings). It is likely that 8-year-old children who attend 2nd grade and learn to read in the shallow Russian orthography rely on the grapheme-phoneme conversion and retain the use of the serial sublexical route of reading, similarly to young children learning to read in other shallow orthographies (Carioti et al., 2021).

Present study

To the best of our knowledge, there is no available research yet that, apart from looking at the standard word-level eye-movement measures, also examines the global reading processes between children with and without reading difficulties. In this study, we aim to fill this gap by (1) examining basic eye-movement measures in reading simple Russian sentences and (2) comparing the development of global reading processes in grades 1 through 5 in two groups of Russian-speaking children: typically developing (control) group and the high risk of developmental dyslexia group. We deliberately avoided the direct labeling of the latter group as "readers with dyslexia" as only 40% of the children in that group received an official DD diagnosis (see the "Method" section for details).

In sum, we seek to answer the following research questions:

1) Do groups differ quantitatively in the basic eye-movement characteristics? If yes, do observed differences sustain from grades 1 to 5?
2) What are the common global reading processes in children with and without reading difficulties when they read simple sentences in Russian?
3) How do the preferences for one or another reading process change in both groups of children from the 1st to the 5th grade?

Based on the previous research in Russian-speaking children with dyslexia (Alexeeva et al., 2020; Kornev et al., 2019) and other languages with shallow orthographies (e.g., MacKeben et al., 2004), we hypothesize that the high-risk group will read slower in all duration measures (First Fixation Duration, Single Fixation Duration, Gaze Duration, and Total Time reading) compared to the control group throughout all school grades. We also expect higher regression and lower skipping probabilities in the high-risk group, but it is likely that these differences disappear as children become older (based on the findings in Kornev et al., 2019) and the main difference between the groups will be limited to the reading speed reflected in fixation durations.

In respect to scanpath reading processes in children who are at the high risk of DD, this study is more exploratory in nature. The findings should, however, parallel the results of eye-movement analysis to some extent. We hypothesize that in the first grade, both groups of children will adopt a reading process similar to the beginner process identified in Parshina et al., (2021): long fixations on the word, multiple rereadings of the words, and the entire sentences. It is likely that children in the high-risk group will still engage in the beginner-like reading processes in the second grade, whereas the control group will "move up" to the intermediate-like reading process with more skipping and fewer long regressions or sentence rereadings. The fluent-like reading process (short fixation durations, very few word rereadings, and more skipping) should be increasingly present in the control group starting with the third grade and be prevalent in the 5th grade. Whether the fluent process is "achievable" by the high-risk group in general remains uncertain.

The data, script, supplementary tables, and figures for this study are freely available at the Open Science Framework project page https://osf.io/wmj4g/

Method

Participants

One hundred forty-four Russian-speaking school students from grades 1 to 5 took part in the study (54 girls, $M_{age} = 9.4$, $SD = 1.19$). Seventy-two children from the high risk of DD group was matched with children from control group on one-on-one basis by gender and grade ($M_{age\ high\text{-}risk} = 9.47$, $SD = 1.24$; $M_{age\ controls} = 9.35$, $SD = 1.14$; $N_{1st\ grade} = 8$, $N_{2nd} = 10$, $N_{3rd} = 20$, $N_{4th} = 28$, $N_{5th} = 6$). The children were identified as at high risk of DD or typically developing according to the Standardized Assessment of Reading Skills in Russian (SARS, Kornev, 1997) that is commonly used to assess reading fluency and comprehension in Russia (Dorofeeva et al., 2019). The children were asked to read a text aloud as quickly and accurately as possible and to answer ten comprehension questions. According to the guidelines of SARS, the number of words read correctly in the first minute serves as a reading fluency measure, while the number of correct answers serves as a reading comprehension assessment. The reading speed of all 72 children in the high-risk group was below 1.5 *SD* from the mean according to the updated normative data (Dorofeeva et al., 2019). Additionally, twenty nine children in the high-risk group were diagnosed with dyslexia by a speech-language pathologist at the Center for Speech Pathology and Neurorehabilitation, Moscow, Russia. Their diagnoses varied from mild to severe dyslexia with phonological impairment. Children with the diagnosis and children who did not receive an official diagnosis but were assigned to the high-risk group did not differ in reading fluency or reading comprehension (see Table A in the Supplementary Materials for the model output). All children in the high-risk and DD groups had normal hearing and fell within normal range on the nonverbal fluid intelligence test (Raven's Colored Progressive Matrices, Raven et al., 2003). The parents or primary caretakers of all participants signed an informed consent form before the start of the study.

Additionally, we assessed children's phonological awareness using the Russian Test of Phonological Processing (RuTOPP, Dorofeeva et al., 2020) (see Table 1 for average scores for performance on reading assessment and phonological awareness tasks). In the phoneme detection task, the children heard a phoneme followed by a word and were asked to decide whether the phoneme was present in the word by pressing yes/no keys on the tablet. In the changing sound pseudoword task, the children were asked to replace a specific phoneme in an auditorily presented pseudoword with another phoneme (e.g., in the trial "Replace the sound /v'/ with /v/ in the "*mimiv'a*" the correct response is "*mimiva*"). We calculated the proportion of correct responses in both tasks. Again, children with the dyslexia diagnosis and children without it did not differ in the performance on the phoneme detection task, but in the changing sound task, the former group replaced correctly considerably fewer phonemes (see Table A in the Supplementary Materials for the model output).

Materials

The eye-tracking reading task consisted of 30 sentences comprising the child version (Korneev et al., 2017) of the Russian Sentence Corpus (Laurinavichyute et al., 2019). All sentences in the corpus were adapted in complexity for 8–9-year-old children and contained various grammatical structures typical for Russian language (SVO and OVS word orders, active and passive constructions, relative clauses, etc.), as illustrated in Examples (1)–(2). On average, sentences consisted of 8 words (range 6–9), and the words were 5.6 letters long (range 1–13). All words in the corpus were annotated for length and frequency (Lyashevskaya & Sharov, 2009).

(1) Item	В магазине	Андрей	купил	молоко,	сметану,	творог
Transliteration	v magazine	Andrey	kupil	moloko	smetanu	tvorog
Gloss	in store	Andrey	bought	milk	sour cream	cottage cheese
Translation	"In the store Andrey bought milk, sour cream, cottage cheese."					

Table 1 Participant characteristics and average scores for performance on reading assessments and phonological awareness tasks (SDs)

	High-risk group		Control group
	Diagnosed	Non-diagnosed	
N	29	43	72
Gender	10 girls	17 girls	27 girls
SARS: reading fluency (count)	50.8 (27.7)	45.7 (19.6)	103.2 (30)
SARS: comprehension (count)	7.7 (2.4)	7.7 (1.7)	8.7 (1.3)
Phoneme detection task (%)	90 (9)	87 (10)	92 (9)
Changing sound task (%)	74 (21)	64 (21)	83 (15)

(2) Item	Брошенный	мальчиком	снежок	попал	в окно	второго	этажа
Transliteration	broshennuy	mal'chikom	snezhok	popal	v okno	vtorogo	etazha
Gloss	thrown	boy$_{PASS}$	snowball	got in window		second	floor
Translation	"A snowball thrown by a boy hit the second-floor window"						

Procedure

Eye movements were recorded using an EyeLink 1000+or an EyeLink Portable Duo (SR Research) eye tracker with a 1000-Hz sampling rate. Participants positioned approximately 70 cm away from the screen, with their head stabilized on a chinrest. By default, the right eye was recorded. First, a 9-point grid calibration was performed. Then, the participants were instructed to read silently, at a comfortable pace starting with 3 practice trials. The sentences were presented in a random order, and 3rd of all sentences were followed by comprehension questions with 2 response options.

Each trial started with the drift correction (black dot in the space of the first letter of the first word), and in case the correction was successful, the sentence appeared on the screen (Ubuntu Mono, 30, black). After reading the sentence, participants were instructed to fixate a red circle in the bottom right corner of the screen. The fixation triggered either the next trial or a comprehension question. Overall, the reading task took approximately 40 minutes to complete.

Data analysis

The data analysis consisted of three stages. First, we calculated and compared the conventional word-level eye-movement measures (*FFD* — First Fixation Duration, *SFD* — Single Fixation Duration, *GD* — Gaze Duration, *TT* — Total Time reading, skipping, and regression probabilities) between the control and high-risk groups using a series of (generalized) linear mixed-effects models. To identify global reading processes, in the second stage, we followed the same five steps of scanpath data analysis as in Parshina et al., (2021), we briefly describe each step below. In the final third stage of analysis, we ran a generalized linear mixed-effects model to investigate whether reading processes differ between the control and high-risk groups in each grade. The script and the supplementary materials with scanpath figures are available at the Open Science Framework project page https://osf.io/wmj4g/.

Plotting scanpaths for each sentence and participant As the first step in scanpath analysis, we created scanpath visualizations for all children in each sentence by plotting eye-movement fixation sequences using the x- and y-coordinate and duration of each fixation. Figure 2 represents scanpaths coded by color for each group (red — high-risk, green — control) produced for the sentence in Example (1), the easiest sentence to read (according to the (dis)similarity measure by von der Malsburg & Vasishth, 2011, see below). In Fig. 2, we can see that with the exception of few children, in general the participants read in a similar way: They fixated most of the words but did not produce many regressions. The most prominent difference was in the speed of reading (i.e., the line is extended vertically more in some scanpaths; see file S1 for the scanpath plots for all the sentences in the Supplementary Materials).

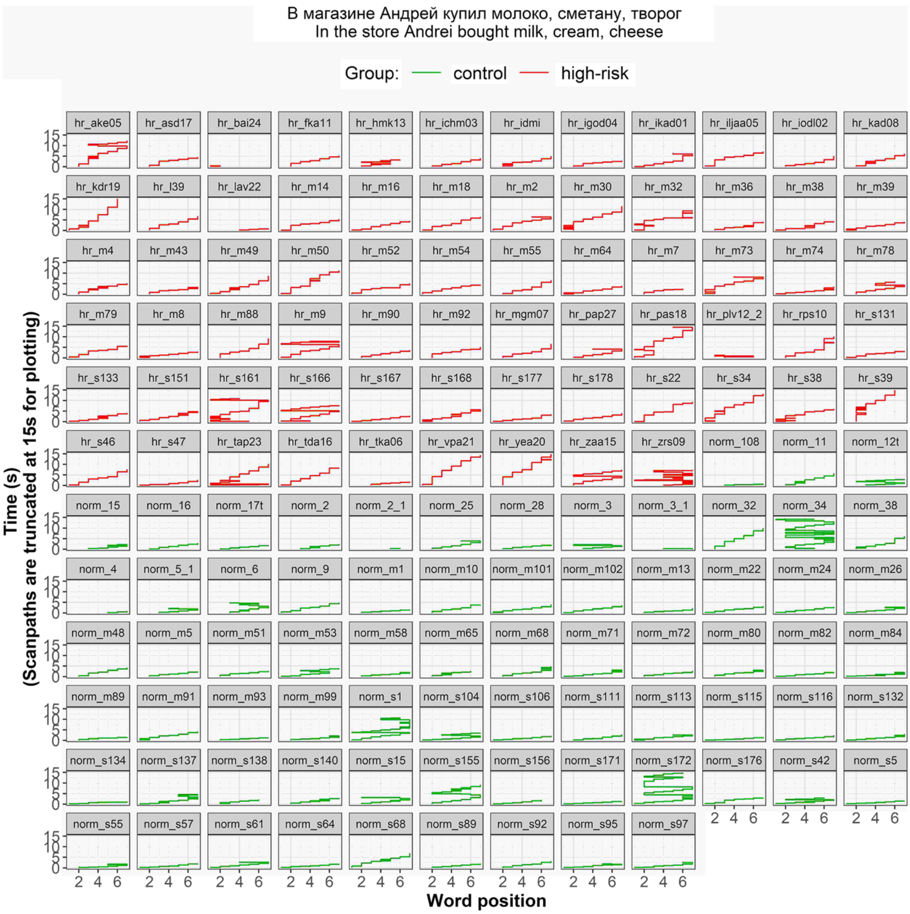

Fig. 2 Scanpaths for the sentence in Example (1) color-coded by group

Calculating the pairwise dissimilarity scores As the next step, for every sentence, we compared how similar each scanpath was to all other scanpaths. In other words, this step estimates how much the fixation sequence of one child reading the sentence is different or similar to the fixation sequence of another child reading the same sentence. To that end, we used the software package *scanpath* for R (von der Malsburg et al., 2015) with implemented dissimilarity score calculation: The formula calculates the difference in the location (the x- and y-coordinates as continuous variables) and duration of two sequentially aligned fixations in all scanpaths in a pairwise manner, creating a matrix of the difference scores (see von der Malsburg & Vasishth, 2011 for details).

Fitting maps of scanpaths Next, to get a general idea how similar or different were the children's scanpaths in each sentence, we calculated scanpath maps using multi-dimensional scaling (Kruskal, 1964). Each scanpath is plotted as a point on this map, and its location corresponds to the dissimilarity score obtained in the previous step. The closer the two scanpaths are, the more similar the reading patterns are of the two children. Figure 3 represents the map for Example (1).

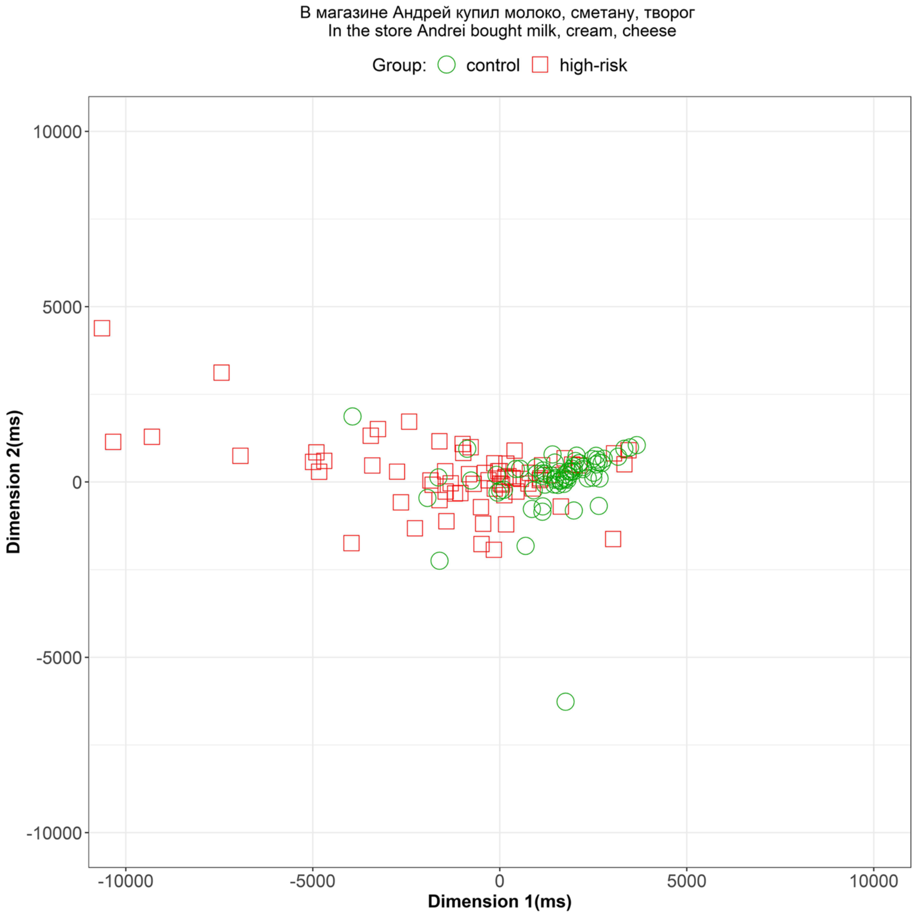

Fig. 3 Maps of scanpaths for Example (1)

The dimensions of the map can correspond to various reading characteristics (e.g., speed, word skipping, number or length of regressions, number of fixations, etc.), and the number of dimensions determines how well the map represents the scanpath dissimilarity. The higher number of dimensions will result in a better fit (i.e., more variance explained), but it is important not to overfit the data and not to have dimensions that are uninterpretable. We fitted the maps with 7 dimensions for each sentence which resulted in the maps that on average can explain 88% ($SD = 0.89$) of the variance. Maps of scanpaths were fitted using the *isoMDS* function in the R package MASS (Venables & Ripley, 2002). (See Figure S2 for the scanpath maps for all the sentences in the Supplementary Materials.)

Cluster analysis Next, for each sentence, we applied the Gaussian mixture modeling (*Mclust* package, Fraley & Raftery, 2007) to identify the clusters of scanpaths with qualitatively similar reading characteristics. This procedure not only allows to detect intersecting clusters but also is able to calculate the optimal number of clusters for each sentence. The mean number of clusters for all sentences was 4.6 ($SD = 1.1$, range 3–8). For the ease of interpretation, we then fitted the models with 5 Gaussians for all sentences in the corpus.

(See Figure S3 for maps of the scanpath clusters for all the sentences in the Supplementary Materials.) Fig. 4 presents scanpaths for Example (1) again, but now colors represent clusters to which each scanpath was assigned as defined by the Gaussian mixture modeling.

Identifying prototypical scanpath reading processes As the last step in scanpath analysis, we determined which scanpath was the most representative of each of the five clusters in the sentence. To do that, we calculated the distance between each scanpath on a map and the cluster's centroid and then selected the scanpaths which were the closest to the cluster's center. As a result, for each sentence in the corpus, we obtained five 'prototypical' reading processes. Although each sentence has a set of different five processes (see File S4 for the prototypical scanpath reading processes for all the sentences in the Supplementary Materials), they shared similar characteristics best represented by the processes in Fig. 5, elicited by the sentence in Example (2).

The first three processes (fluent, advanced, and upper-intermediate, panels A, B, and C in the Fig. 5, respectively) include scanpaths that share very similar reading characteristics:

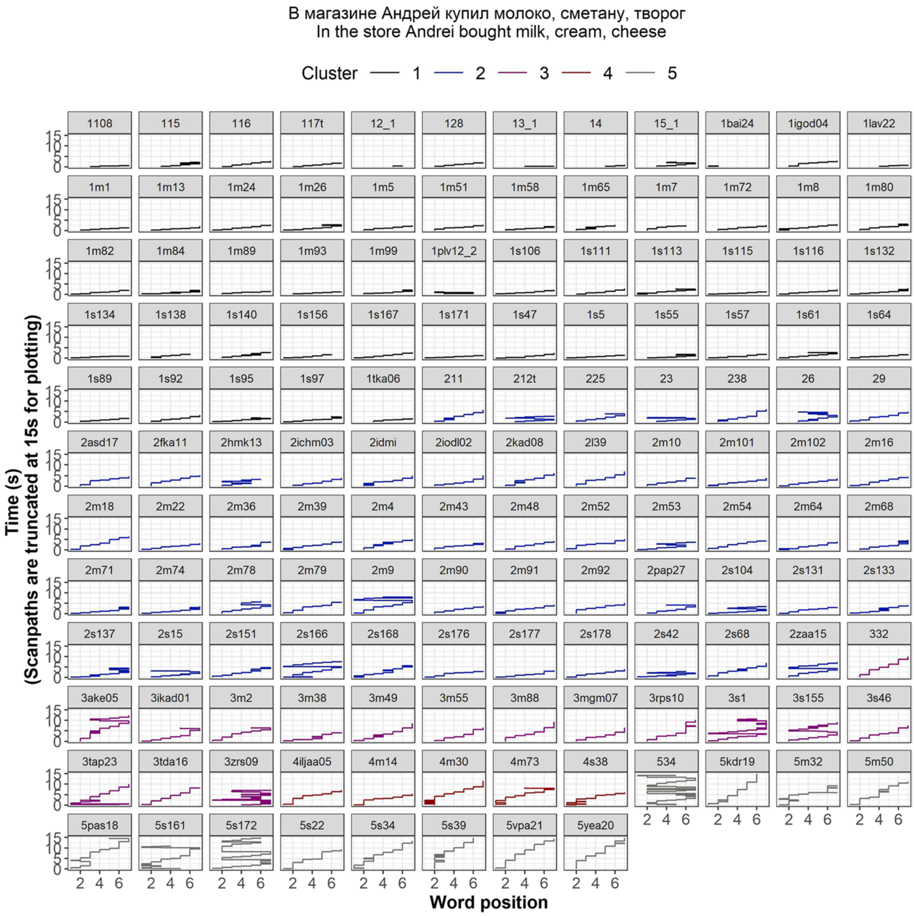

Fig. 4 Scanpaths for Example (1) color-coded by cluster assignment

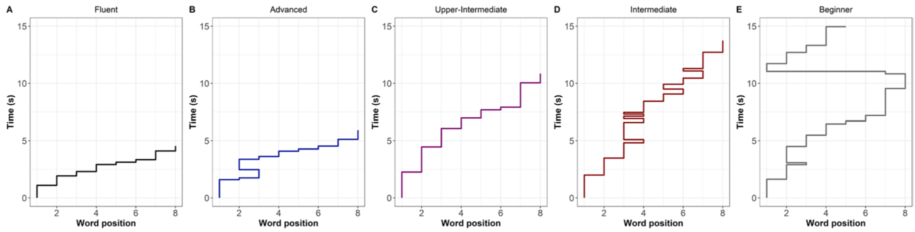

Fig. 5 Prototypical reading processes represented by the scanpaths closest to the clusters' centroid for one of the sentences in the corpus (Example (2)). **A** fluent, **B** advanced, **C** upper-intermediate, **D** intermediate, **E** beginner

they all represent reading patterns with very few regressions and some skipping (not depicted in prototypes in Fig. 5). The main difference between these three processes is the speed of reading with the fluent process being the fastest and the upper-intermediate process being the slowest. The fourth intermediate process (panel D, Fig. 5) is characterized by the increase in fixation durations, fewer skipping instances, and more importantly, multiple word-rereading within the first-pass reading. Finally, the last beginner reading process (panel E, Fig. 5) reflects the reading process that has the longest total reading time resulting from the increased fixation durations, word rereading, and multiple rereading of the entire sentence.

Results

Recall that our data analysis is implemented in three stages: (1) to compare the conventional eye-movement characteristics (fixation durations, skipping, and regression probabilities) between the control and high-risk group of readers; (2) to identify prototypical reading processes for all readers in the study (performed in the scanpath data analysis section above); and (3) to investigate whether the readers' group (control vs. high-risk) and their grade determine which scanpath reading process the reader adopts. Below, we report the results of stages 1 and 3.

Eye-movement measures: descriptive statistics and between-group comparison

For all analyses, fixations and saccades were extracted from eye-movement data according to the algorithm from the Data Viewer package (SR Research Ltd). All fixations less than 100 ms were excluded from the analysis, but no upper cutoff limits were applied. The average accuracy for comprehension questions was 90% ($SD = 31$) for the control group and 83% ($SD = 37$) for the high-risk group.

Table 2 presents means and standard deviations for all eye-movement measures for both groups. To compare eye movements between groups, we ran a series of (generalized) mixed-effects linear models with each eye-movement measure as an outcome and group (sum-contrast coded; 1 for control group), grade (continuous), word frequency (log-transformed), word length (centered and scaled), and four two-way interactions (group X length, group X frequency, grade X length, and grade X group) as well as the relative position of the word as fixed predictors. Random structure included random intercepts for participants, sentences, and words. For the (generalized) linear mixed effects models, we used the R

Table 2 Basic parameters of eye movements for time duration measures and probabilities of skipping and regressions (SD in parentheses)

Measure	Control	High-risk
First Fixation Duration (ms)	241(55)	321 (77)
Single Fixation Duration (ms)	281 (79)	368 (118)
Gaze Duration (ms)	464 (206)	982 (420)
Total Time reading (ms)	669 (314)	1467 (718)
Skipping (%)	9 (5)	9 (11)
Regression out (%)	19 (7)	21 (7)

package lme4 (1.1–13). To analyze significant interaction effects, we used the emtrends function in the R package emmeans (Lenth et al., 2021) which contrasts slopes of the predictors in the model. Table B in the Supplementary Materials presents the output for all models.

The (g)lmms indicated that GD, TT, but not FFD measures differed between groups: high-risk group fixated on words for significantly longer time than the control group (all ps < 0.004) and the effect was stronger for longer and less frequent words as shown by the interaction effects (slope contrasts ps < 0.044). In FFD, however, it was the control group who was more sensitive to the word frequency (slope contrast: $Est. = -0.014$, $SE = 0.00$, $z\ ratio = -2.1$, $p < 0.037$), making shorter first fixations on frequent words compared to the high-risk group. In SFD, the significant group and length interaction effect indicated that in the high-risk group, longer words elicited shorter single fixations, whereas the control group had an opposite trend (slope contrast: $Est. = 0.091$, $SE = 0.19$, $z\ ratio = 4.8$, $p < 0.001$).

The grade affected most of the duration measures (FFD, GD, TT): the higher the grade of the participants, the less time they fixated on the words in all duration measures (all ps < 0.001). In SFD, however, the duration decreased significantly as grades increased only in the control group (slope contrast: $Est. = -0.036$, $SE = 0.03$, $z\ ratio = -4.2$, $p < 0.001$). There was also a significant interaction between the group and the grade on the skipping probability: While the skipping probability increased in reading from younger to older children in the control group, it plummeted in the high-risk group (slope contrast: $Est. = 0.508$, $SE = 0.14$, $z\ ratio = 3.6$, $p = 0.003$). In addition, children in the high-risk group did not skip short words as much as children in the control group (slope contrast: $Est. = -0.656$, $SE = 0.09$, $z\ ratio = -6.9$, $p < 0.001$).

There was no main effect of group on the regression probability, but there was a significant interaction between grade and word frequency and between group and word length. Specifically, regression probability decreased as grades increased, but more for high-frequency words than for low-frequency words. In the high-risk group, longer words elicited higher probability of making a regression out, while for the control group, the length did not matter (slope contrast: $Est. = 0.841$, $SE = 0.07$, $z\ ratio = -1.9$, $p = 0.05$).

Can group and/or grade determine the scanpath reading processes?

In this stage of analysis, we examined whether the reader's group and grade can predict which of the five reading processes the reader will adopt for a given sentence. We ran a series of binomial mixed-effects model for the five scanpath reading processes wherein each reading process was binary-coded ("1" = scanpath of a participant belongs to the process, “0” = scanpath does not belong), the group was sum-contrast coded (1 for the control group), and the grade was entered as a continuous predictor. All GLMMs included a scanpath reading process as an outcome; group, grade, and their interaction as the fixed predictors and sentences; and participants as random intercepts. We used *sjPlot* package 2.8.3 for data visualization and the computation of *p*-values (Lüdecke, 2017).

The results are presented in Table 3 ($N_{participants} = 144$, $N_{sentences} = 30$, observations: 4228). They indicate that there was a main effect of group for three out of five processes and that the grade was a significant predictor for all five reading processes: Children in the higher grades were more likely to adopt fluent or advanced processes, whereas younger readers engaged in the other three reading processes more often. The children in the high-risk group showed a higher probability of following the beginner reading processes compared to the control group. Other significant group main effects are interpreted in combination with the interaction effects with the grade.

To unpack significant interaction terms between group and grade predictors for the first four processes, we re-coded the grade predictor as a factor with 5 levels and used the R package emmeans (Lenth et al., 2021) for calculating all pairwise comparisons (Bonferroni correction applied) among groups and grades. The results indicated that for the fluent process, there was no difference between the groups in the 1st and 2nd grade (ps = 1.00), but starting with the 3rd grade and up, the control group was engaging in the fluent process increasingly more frequently than the high-risk group (ps < 0.002). For the advanced process, the situation is the opposite: The groups did not differ in 3rd, 4th, or 5th grade (ps > 0.10), but the high-risk readers produced significantly lower probability of adopting the advanced process in the 1st and 2nd grades compared to the control group. Next, the control group were increasingly less likely to adopt the upper-intermediate reading process in 3rd–5th grades but again, did not differ in the probabilities with the high-risk group in the 1st or 2nd grades. In the intermediate reading process, the groups were similar only in the 1st grade ($p = 1.0$), after that the high-risk group engaged in the intermediate process significantly more often (all ps < 0.050). Figure 6 presents interaction plots for all reading processes.

In general, the following picture emerges: In the control group, as children are enrolled in the higher grades, the probability of adopting the more “progressive” reading process steadily increases, whereas the situation in the high-risk group is not as straightforward. Even in the 5th grade, children in the high-risk group mostly engage in the advanced reading process and almost never read according to the fluent process. They primarily rely on the upper-intermediate and intermediate process in 2nd–4th grades and on the beginner reading process in the 1st grade. Notably, the probability of engaging in each respective process between high-risk readers in 2nd to 5th grades and the 1st-grade control readers did not differ across all five reading processes (all ps > 0.428).

Discussion

In this study, we compared eye movements during reading simple sentences in Russian children with high risk of DD and typically developing children from grades 1 to 5. We had three research questions and, accordingly, three stages of analysis. We started with the comparison of the conventional word-level eye-movement measures between the groups. Then, using the scanpath approach, we identified global reading processes that children adopt when reading sentences in Russian. Finally, we compared the preference of reading

Table 3 Parameter estimates for generalized linear mixed models: Probability of adopting the scanpath reading process by group and grade

	Fluent			**Advanced**			**Upper-intermediate**			**Intermediate**			**Beginner**		
Fixed effects	*Odds ratio*	*SE*	*p*	*Odds ratio*	*SE*	*p*	*Odds ratio*	*SE*	*p*	*Odds ratio*	*SE*	*p*	*Odds ratio*	*SE*	*p*
(Intercept)	0.008	0.005	< 0.001	0.100	0.033	< 0.001	0.405	0.102	0.001	0.423	0.117	0.004	0.331	0.157	0.026
Group (ctrl)	0.922	0.511	0.883	6.53	1.93	< 0.001	1.72	0.379	0.014	0.994	0.230	0.979	0.332	0.151	0.026
Grade	2.03	0.328	< 0.001	1.35	0.115	< 0.001	0.808	0.053	0.002	0.679	0.048	< 0.001	0.414	0.064	< 0.001
Group * Grade	1.70	0.274	0.001	0.632	0.054	< 0.001	0.722	0.048	< 0.001	0.808	0.057	0.004	0.852	0.129	0.290
Random effects															
σ^2	3.29														
$\tau_{00participant}$	3.35			0.91			0.51			0.55			2.03		
$\tau_{00sentence}$	0.92			0.51			0.45			0.69			0.49		
Cond. R^2	0.706			0.367			0.298			0.372			0.648		

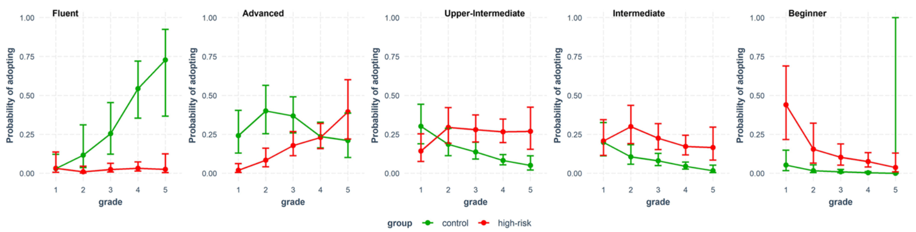

Fig. 6 The probability of engaging in the scanpath reading processes as a function of the group and grade based on the estimated marginal means from the models

processes by two groups of readers and identified the changes in these preferences across school grades. In what follows, we separately discuss the findings in respect to each research question.

What are the quantitative differences in the conventional eye-movement measures and how do they change across the grades?

In general, we found that the main difference in the eye-movement measures between the groups was the reading speed reflected in longer fixation durations (Gaze Duration and Total Time reading) for the high-risk group compared to the control group and that the effects are more pronounced for longer and less frequent words. These findings are consistent with what we already know about reading in children with DD in previous research in Russian, German, Italian, or Spanish (Alexeeva et al., 2020; Korneev et al., 2019; MacKeben et al., 2004; Suárez-Coalla & Cuetos, 2012; Trauzettel-Klosinski et al., 2010).

Our findings in respect to Single Fixation Duration measure in the high-risk group were somewhat unexpected: The children with the high risk of DD produced shorter single fixations on longer words. We suggest that the reading strategy of the children in the high-risk group might explain the result. First, only 16% of all words in the corpus were fixated only once (vs. 30% in the control group). Thus, children with reading difficulties in general need more fixations for the initial word recognition. Second, as we know that children with DD struggle with decoding long words much more than typically developing children (Kirkby et al., 2008), it is likely that they "avoid" reading these words altogether and hence choose the strategy of briefly fixating them once and then proceeding further in the text. This explanation is also consistent with the findings of the previous research that children with DD are not as efficient in processing parafoveal information as typically developing children are (Barrington, 2019; Jones et al., 2013; Rayner, Murphy, et al., 1989; Rayner, Sereno, et al., 1989; Silva et al., 2016; Yan et al., 2013). Hence, instead of performing initial lexical pre-processing of the long word in parafovea, they might estimate the time and cognitive effort needed to process the word and judge that it would be more efficient to perform a "quick check" strategy by fixating it once for a short time.

For Total Time reading and Gaze Duration measures, the differences we observed sustained from the 1st to the 5th grade: The children in the high-risk group always fixated words for longer times than the control group of children, although with age the fixation durations decreased in both groups. We did not find the same to be true for the Single Fixation Duration measure. The children in the high-risk group produced similar durations throughout all grades while typically developing children fixated for shorter times in the higher grades. Furthermore, the skipping probability "developed" differently in two groups. The control group exhibited higher skipping probability in the higher grades, while the effect was reversed for the high-risk group: The skipping probability decreased drastically from grades 1 to 5. We suggest that the trends in these earliest eye-movement measures (i.e., skipping and single fixation duration) again reflect difficulties in the initial word recognition (Rayner, Murphy, et al., 1989; Rayner, Sereno, et al., 1989). It seems that in the first grade, children with reading difficulties experience greater challenges in the grapheme-phoneme decoding compared to their typically developing peers. With age (and perhaps with metacognitive understanding of their reading difficulties), children rely more on the serial letter-by-letter processing to gain a more efficient grapheme-phoneme decoding process which is reflected in less skipping and longer fixations.

Finally, we did not find the group or grade differences in the regression probability. This finding confirms the results of the previous research in shallow orthographies that reported readers with dyslexia to produce very few regressions, similarly to typically developing readers (De Luca et al., 1999, 2002; Hutzler & Wimmer, 2004; Kornev et al., 2019 in older group). According to Hutzler and Wimmer (2004), the reason for low regression instances is in the consistent grapheme-phoneme correspondence in orthographies such as Russian. In particular, children with dyslexia who read in shallow orthographies generally produce fewer misreadings compared to children who read in English or French resulting in fewer occasions of word rereadings and, therefore, easier process of the global information integration.

Which global reading processes children adopt in reading sentences?

After we compared basic eye-movement measures in reading in two groups of children, the next goal was to identify the common global reading processes that children engage in when reading simple sentences in Russian. The reading processes were identified via a scanpath approach that includes plotting and comparing reading patterns based on their dissimilarity scores which was then followed by the cluster analysis (von der Malsburg & Vasishth, 2011). This method allowed us to (1) visualize eye-movement sequences across the entire sentences and (2) statistically investigate the similarities and differences between scanpaths of readers from different groups and grades. As a result, we identified five global reading processes that children engaged in while reading sentences in Russian.

The first fluent reading process is the similar process to one that was identified in Parshina et al., (2021) as the reading strategy preferred by adult native speakers of Russian. It represents fast and efficient reading skills without any noticeable difficulties in word recognition or general comprehension. The main characteristics of the fluent process are short fixation durations (Gaze Duration = 426 ms), some skipping (23%), and very few regressions (14%). It should be noted, however, that although the fluent process in this study is qualitatively similar to the same-titled process in Parshina et al., (2021), in the current analysis it includes considerably longer fixation durations (cf. GD = 289 ms). The next two processes, the advanced and upper-intermediate processes, resemble the fluent process in their characteristics with the main difference being the duration of fixations (GD = 585 ms and GD = 716 ms, respectively). These two processes still include the regular left-to-right reading and few regressions (19% and 20%), but the time that readers spend on each sentence increased. It is intuitive to suggest that these two processes are adopted by readers who are in transition to be an adult-like skilled reader.

The intermediate and beginner reading processes also have been previously identified in Parshina et al., (2021). The intermediate process is characterized by even longer fixation durations (GD = 808 ms) and more short regressions to reread the words (22%) compared to the upper-intermediate process. In the previous study, this process was mostly adopted by Russian-speaking second-graders which authors suggested was linked to the "local" difficulties with word recognition (i.e., grapheme-phoneme conversion) and caused readers to go back and reread the words multiple times.

The beginner reading process, on the other hand, apart from local difficulties, signaled the "global" difficulties in information integration and general comprehension reflected in multiple rereadings of the entire sentences (regression probability = 26%, each word was reread on average 3 times, GD = 1004 ms, sentence reading time = 20 s). In Parshina et al., (2021), this process was the preferred choice for readers who were at the very beginning of literacy development (e.g., low-proficiency bilinguals). In this study, children in the high-risk group always (i.e., regardless of the grade) had the higher probability of adopting the beginner reading process compared to the children in the control group. All other group effects were dependent on the school grade, the finding that we discuss in the section below.

How do reading processes change between and within groups in grades 1 to 5?

As the final step, we investigated what reading processes children in two groups adopt in each grade and whether these preferences change as children are enrolled in the higher grades. In general, we saw that children in the control group in the 1st grade started with the upper-intermediate process and then progressed quickly to the advanced process. In the 4th grade, they read mostly relying on the fluent reading process and continue to do so in the 5th grade.

In the high-risk group, first-graders started with the beginner reading process and then switched to the intermediate or upper-intermediate reading processes in the 2nd grade. In the 3rd and 4th grades, they still engaged mostly in the upper-intermediate process. Finally, in the 5th grade, the preference for the reading process changed to the advanced one. To summarize, in the global reading processes as assessed via scanpath patterns, children in the high-risk group of DD in the 2nd, 3rd, and 4th grades read on par with 1st-grade children in the control group. Fifth graders in the high-risk group produced reading patterns that were qualitatively similar to reading patterns of the 2nd-grade typically developing peers, suggesting that in global reading processes children in the high-risk group "lag behind" the control group by 2–3 grades.

Of course, these results do not mean that none of the children in the high-risk group adopted the fluent reading strategy or that children only used one strategy across all sentences. In fact, Fig. 7 confirms that both children with diagnosed and non-diagnosed dyslexia read according to multiple processes, typically showing stronger preferences for one or two of them. Besides grade, such variability among participants and across sentences is likely due to the individual differences in the speed of the lexical access and general reading fluency of the participants as well as the lexical characteristics of the words in the sentence (such as length, subjective and objective frequency, predictability, age of acquisition, orthographic and morphological complexity). Thus, reading processes that we identified in this study, even within an individual reader, do not represent stagnant reading strategies but rather flexible patterns that readers adapt for the efficient written language comprehension.

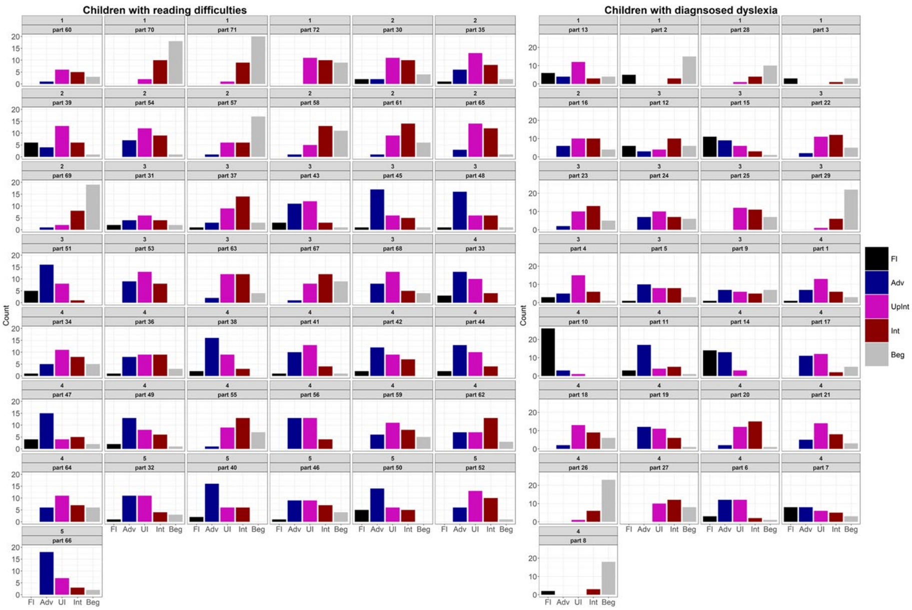

Fig. 7 Individual differences in adopting one of the five global reading processes in the high-risk group. The number on the top refers to the participant's grade

Combining together with the analysis of the word-level eye-movement measures, the results of the global reading processes draw a clear picture. In the first stage of analysis, we saw that children differed quantitatively within and between groups in fixation durations (SFD, GD, TT) throughout the grades and skipping probability in some grades. The scan-path analysis, however, indicated that global reading processes did not differ qualitatively in the high-risk group from the 2nd to the 4th grade, and moreover, they were similar to the reading processes of the children in the 1st grade in the control group. Furthermore, although children in the high-risk group did not generally adopt the fluent reading process, it should be noted that the scanpaths of the advanced reading processes (preferred in the 5th grade) had a very similar structure to the fluent one (the difference was in the reading speed): Both processes include few local regressions, absence of global regressions to reread sentences, some skipping instances, and shorter fixation durations compared to the other processes.

The obtained results support the claim that the gap between the two groups is indicative of the reading delay (Hyönä & Olson, 1995; Rayner, 1985a, b), but the global reading strategies and their qualitative development as children become older are underlyingly similar for both groups. What is different is the timeframe of this development. The typically developing children move through the continuum of reading processes fast and achieve the adult-like patterns (albeit with slower reading speed) by the 5th grade, while the high-risk group stagnates in 2nd–4th grades. Curiously, we found that first graders in the high-risk group start with a qualitatively different reading process than the first-grade typically developing children. Although there was no statistical difference in regression probability in the analysis of the word-level eye-movement measures, first graders in the high-risk group engaged mostly in the beginner reading process that includes the highest probability of regressions (0.26) with scanpaths indicating that many of these regressions constituted sentence rereadings. Thus, it is likely that in the 1st grade, children with reading difficulties have challenges not only at the "local-level" grapheme-phoneme decoding but also with the global sentence interpretation that stem from the delays in the visual word recognition. As the practical application for such results, we suggest that children with dyslexia might benefit from the training programs that aim to improve the speed and accuracy of the visual word recognition starting at the first grade. The potential exercises might involve practicing both the lexical route of reading (e.g., reading words of various complexities) and the phonological route of reading (e.g., reading non-words of various difficulty) on a regular basis.

Limitations and future directions

It should be mentioned that the global reading processes that we identified by extracting the scanpaths closest to the cluster centers are primarily descriptive. In each of the 30 sentences, the prototypical scanpaths shared many common features, but they still varied considerably as they represent the actual reading patterns of an individual. The future research would benefit from a development of scanpath tool that allows to extract the prototypical scanpaths based on the averaged features of all scanpaths in the cluster and eliminate the need for the visual inspection that can be subjective in nature.

We also would like to mention the difference in the results for second-grade typically developing children in this study and in Parshina et al., (2021). We found that our second graders mostly adopt the advanced reading process, whereas their peers in Parshina et al., (2021) primarily engaged in the intermediate reading process. We suggest that the reason for that is related to the method of the participant recruitment. In this study, the data was collected during the pandemic and typically only highly motivated parents/caretakers brought their children to the laboratory (vs. collecting data in schools), which can drive the distribution skewedness to children with either excellent or poor reading skills. It is likely, therefore, that in the current study in general we had the group of children with better reading skills compared to the previous study. This difference should be considered when interpreting the gap between reading processes in readers with and without dyslexia.

Finally, a considerable limitation of the current study is the cross-sectional approach in which we track the changes in the global reading processes by comparing the eye-movement behavior in groups of different children. Although time-consuming, the future research should consider a longitudinal design to observe the true development of the global reading processes and to avoid the influence of individual differences of the participants.

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Declarations

Consent to participate The parents or primary caretakers of all participants signed an informed consent form before the start of the study.

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