INTERNATIONAL LITERACY ASSOCIATION
READING RESEARCH QUARTERLY

Monolingual and Bilingual Reading Processes in Russian: An Exploratory Scanpath Analysis

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ABSTRACT

In the present study, we used a scanpath approach to investigate reading processes and factors that can shape them in monolingual Russian-speaking adults, 8-year-old children, and bilingual Russian-speaking readers. We found that monolingual adults' eye movement patterns exhibited a fluent scanpath reading process, representing effortless processing of the written material: They read straight from left to right at a fast pace, skipped words, and regressed rarely. Both high-proficiency heritage-language speakers' and second graders' eye movement patterns exhibited an intermediate scanpath reading process, characterized by a slower pace, longer fixations, an absence of word skipping, and short regressive saccades. Second-language learners and low-proficiency heritage-language speakers exhibited a beginner reading process that involved the slowest pace, even longer fixations, no word skipping, and frequent rereading of the whole sentence and of particular words. We suggest that unlike intermediate readers who use the respective process to resolve local processing difficulties (e.g., word recognition failure), beginner readers, in addition, experience global-level challenges in semantic and morphosyntactic information integration. Proficiency in Russian for heritage-language speakers and comprehension scores for second-language learners were the only individual difference factors predictive of the scanpath reading process adopted by bilingual speakers. Overall, the scanpath analysis revealed qualitative differences in scanpath reading processes among various groups of readers and thus adds a qualitative dimension to the conventional quantitative evaluation of word-level eye-tracking measures.

Over the last decade, eye tracking has become a widely used methodology in bilingual language reading research (Cop, Dirix, Drieghe, & Duyck, 2017; Cop, Drieghe, & Duyck, 2015; Dirix, Vander Beken, De Bruyne, Brysbaert, & Duyck, 2020; Kang, 2014; Roberts & Siyanova-Chanturia, 2013; Schmidtke & Moro, 2020; Whitford & Titone, 2012). Silent reading without metalinguistic tasks allows the study of written language comprehension in real time and, therefore, in laboratory settings, reflects the closest approach obtainable to the natural reading behavior of bilingual readers. Conventional local quantitative characteristics of eye movements in reading, such as fixation durations and counts, skipping, and regression probabilities, reveal differences between bilingual and monolingual reading behavior, calculated on a word-by-word basis. In the current study, we focused on a previously unexplored approach to bilingual reading, global qualitative differences between bilingual and monolingual readers, which we investigated using a scanpath approach to eye movements in reading.

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Reading Research Quarterly, 0(0)
pp. 1–24 | doi:10.1002/rrq.414

Scanpaths are sequences of eye movements, or gaze trajectories, that extend beyond the word level to the sentence and discourse levels. Specifically, scanpaths constitute sequences of eye gaze positions determined by the *x*- and *y*-coordinates and reflect the precise time frame of each fixation within a sentence or text. In contrast to local word-by-word eye movement measures in reading (for reviews, see Clifton, Staub, & Rayner, 2007; Rayner, Chace, Slattery, & Ashby, 2006; Vasishth, von der Malsburg, & Engelmann, 2013), scanpaths inform about global eye movements at the sentential level. For instance, a scanpath analysis of regressive saccades allows not only the identification of whether a regression has occurred but also the distinguishing between different types of regression (e.g., single, short leftward saccades vs. multiple leftward saccades for reverse reading). Furthermore, reading from left to right or from right to left can produce similar fixation durations, even though they represent different cognitive processes. Scanpaths provide the ability to distinguish between these two reading behaviors because the scanpaths take the whole global sequence of eye movement events into account. Furthermore, scanpaths allow differentiation between various types of word-skipping instances (e.g., skipping followed by rereading, skipping only in the second- or third-pass reading, absence of skipping) and between fixation distributions (e.g., increased fixation durations during first-pass reading, decreased durations throughout subsequent rereadings). Overall, scanpath analyses can render a much more detailed and coherent picture of the qualitative differences between groups of readers than conventional, local eye-tracking metrics alone (see the Data Analysis section for a more concrete description of the scanpath measure).

This global qualitative approach to bilingual reading presents a unique opportunity to bridge the theories of visual lexical access and written language comprehension in bilingualism. The lexical access models of Dijkstra and colleagues (i.e., bilingual interactive activation plus: Dijkstra & van Heuven, 2002; multilink: Dijkstra et al., 2019) predict delayed lexical access in reading in bilinguals with low second-language (L2) proficiency levels. It is manifested in early-stage processing measures, specifically less word skipping and longer fixation durations (Roberts & Siyanova-Chanturia, 2013; Whitford, Pivneva, & Titone, 2016). These measures, however, do not address the question of whether delayed lexical access has repercussions for parsing of an entire sentence. The scanpath approach, in contrast, is ideal for detecting any such implications in global eye movement behavior, as it can identify eye movement patterns at the later stages of sentence comprehension and visualize connections to the eye movement patterns at the early stages of processing (e.g., a specific regression pattern to a problematic word). At the same time, a scanpath approach can inform theories of bilingual sentence processing, such as the shallow structure hypothesis (Clahsen & Felser, 2006), the good-enough parsing account (Ferreira, Bailey, & Ferraro, 2002), or the accounts that emphasize the failure in memory retrieval operations (Cunnings, 2017; Van Dyke, Johns, & Kukona, 2014). Although our goal in this exploratory study was not to tackle any specific theory, the scanpath approach allowed us visually and qualitatively to evaluate the word recognition and sentence-processing stages simultaneously. The scanpath approach therefore provided us with a novel tool to investigate reading behavior from the perspective of both the bilingual lexical access and the language comprehension theories in parallel.

The scanpath approach can also play a critical role in distinguishing various types of global gaze trajectories that are frequently characteristic of a participant or a group of participants: We refer to these types as *scanpath reading processes*. We define this term as a recurrent pattern of gaze trajectories at the sentence level, characterized by the specific time frames and locations of fixations, word skipping, and rereadings of the words, phrases, or sentences. This is in contrast to reading comprehension strategies (e.g., McNamara, 2007) that reflect readers' metacognitive efforts to understand the text and that has been extensively investigated in educational research on bilingual reading (e.g., Comer, 2012; K.S. Goodman, 1979; Y.M. Goodman, 1996; Jiménez, García, & Pearson, 1996; Sheorey & Mokhtari, 2001; Stevenson, Schoonen, & Glopper, 2003). Although these concepts are likely related, they focus on different aspects underlying comprehension strategies versus overt reading behavior.

In this study, we focused specifically on the scanpath reading processes exhibited by a group of readers that could enable us to distinguish their eye movement reading behavior from that of other groups. Thus, we establish and qualitatively describe three separate scanpath reading processes that occur in silent, uninterrupted reading without metacognitive tasks in two groups (adults and children) of monolingual readers and two groups of bilingual readers—heritage-language speakers (HSs; bilinguals acquiring the minority language at home and then switching to the majority language in later childhood) and L2 learners (bilinguals learning the L2 through formal education)—when they read isolated Russian sentences. We addressed two main research questions:

1. What scanpath reading processes do readers engage in when reading simple sentences in Russian?
2. How does group membership (i.e., monolingual adults, children, L2 learners, HSs) determine which scanpath reading processes a reader engages in to decode written sentences efficiently?

We start with an overview of eye-tracking research that introduced the scanpath approach. Then, we discuss what is already known about scanpaths in bilingual reading and about eye movement characteristics in reading by monolingual adults, children, HSs, and L2 learners of Russian. We conclude the introduction by presenting some basic information concerning the Cyrillic writing system and the complexities it creates for bilingual speakers who learn to read in Russian.

Written Language Comprehension: A Scanpath Approach

Monolingual Readers

Since the seminal work of Yarbus (1967), researchers have repeatedly used specific eye movement sequences (i.e., scanpaths) to test written language comprehension. One example is the interpretation of temporarily ambiguous sentences (Frazier & Rayner, 1982; Meseguer, Carreiras, & Clifton, 2002; Mitchell, Shen, Green, & Hodgson, 2008). The focus of the analyses in these studies was on individual, local regressive saccades (i.e., backward eye movements to revisit particular sentence regions) with the goal of investigating how participants recovered from the ambiguity once disambiguating information became available. This research, however, did not consider more complex and global-level spatiotemporal eye movement patterns, which limited the researchers' ability to draw conclusions. To address the limitation of the early approaches, von der Malsburg and colleagues (von der Malsburg, Kliegl, & Vasishth, 2015; von der Malsburg & Vasishth, 2011, 2013) devised and applied a new scanpath analysis technique that took into account the full spatial and temporal characteristics of the eye movement sequences over the entire sentence to detect the scanpath reading patterns (called *strategies* in these studies).

Von der Malsburg and Vasishth (2011) started by reexamining the data in Meseguer et al.'s (2002) study and used a scanpath-clustering procedure that revealed functionally different types of eye movement sequences: rereading of the whole sentence (this pattern had gone unnoticed in the more conventional analysis used in the original study by Meseguer et al.) and checking (rapid saccades from the end of the sentence to the disambiguating word). Von der Malsburg and Vasishth also reported that participants varied considerably in their choice of reanalysis strategies, and hypothesized that individual differences, such as working memory capacity, might play some role in determining the strategy preference (cf. time out hypothesis; Mitchell et al., 2008). In a follow-up study with Spanish-speaking participants (von der Malsburg & Vasishth, 2013), the same type of analysis confirmed the previously found scanpath categories and revealed an additional pattern of rapid backward saccades to reread individual words after participants encountered the disambiguating region. This study also measured the working memory ability of the participants as a potential predictor of their reading strategy. Somewhat surprisingly, participants with high working memory capacity produced more regressive eye movements in response to disambiguation than did low-capacity readers, indicating that the former had greater difficulty in processing temporarily ambiguous sentences. The researchers interpreted this in accordance with the good-enough parsing account (Ferreira et al., 2002): Unlike readers with high memory capacity, low-capacity participants did not immediately commit to one of the two available sentence interpretations, thus leaving the sentence interpretation initially underspecified. As a result, low-capacity readers did not have to reanalyze the sentence when they encountered the disambiguating word (for an investigation of the relation between memory and reading patterns at the text level, see Dirix et al., 2020; Hyönä, Lorch, & Kaakinen, 2002).

More recently, von der Malsburg et al. (2015) confirmed the sensitivity of the newly developed (von der Malsburg & Vasishth, 2011) scanpath analysis to factors that are known to influence conventional eye-tracking measures, such as word length (Clifton et al., 2007), syntactic processing difficulty (Boston, Hale, Kliegl, Patil, & Vasishth, 2008; Boston, Hale, Vasishth, & Kliegl, 2011; Demberg & Keller, 2008), and the reader's age (Kliegl, Grabner, Rolfs, & Engbert, 2004; Whitford & Titone, 2017). Collectively, the results of these studies suggested that the scanpath approach might also be a useful method for investigating global reading processes in different populations of participants, including not only skilled monolingual adult readers but also developing readers, both monolingual and bilingual.

L2 Learners

To the best of our knowledge, the only study that has examined bilingual reading using a scanpath approach was Godfroid et al.'s (2015). Twenty L2 learners of English and 20 native speakers performed a grammaticality judgment task of 68 sentences, in which half contained violations in various grammatical structures. The task was administered under two conditions, with and without time limits. Using iterative visual inspection, Godfroid and colleagues identified three major reading patterns that their participants used to process the sentences, regardless of the group or grammaticality: no regressions, an incomplete reading of the sentence followed by a regression to the beginning of the sentence, and rereading of large portions of the sentence. Based on the finding that time pressure effects were observed only in the L2 group, Godfroid and colleagues suggested that untimed reading in bilingual participants might tap into their explicit knowledge (vs. implicit in timed tasks) and represent a controlled eye movement behavior that participants employed to achieve the most efficient sentence comprehension.

HSs

At present, we are not aware of any studies investigating scanpaths in heritage-language reading. HSs are quite different from typical L2 bilinguals (e.g., the L2 participants in Godfroid et al., 2015). The first difference concerns the timing and the environment of language acquisition: Whereas L2 learners acquire the language in school and university settings, typically after puberty, HSs learn the language at home from their caregivers in a similar way to how monolingual children do. In addition, the mode of acquisition also differs: HSs mostly learn the language in an auditory modality (listening and speaking), whereas L2 learners receive formal instruction both in auditory and visual modalities (reading and writing).

Despite HSs' generally sound command of the spoken language, they are rarely taught literacy at home and often do not read in their heritage language, especially in the case of different orthographies between the dominant (e.g., English) and heritage language (e.g., Russian). According to the divergent attainment trajectory of heritage-language development (Benmamoun, Montrul, & Polinsky, 2013; Montrul, 2008; Polinsky & Scontras, 2020; Scontras, Fuchs, & Polinsky, 2015), the competence growth in heritage languages slows down and eventually stops after the switch to the dominant language. As the switch typically occurs when children start school and the input in the dominant language increases, the divergent attainment trajectory suggests that HSs' language skills freeze at the age of their entry to school. Thus, the main prediction is that the language abilities of adult HSs should resemble those of school-age monolingual children (for a review of reading in children, see Blythe & Joseph, 2011). With respect to literacy and reading skills specifically, the divergent attainment trajectory predicts more similarities in global reading patterns between adult HSs and monolingual children than between HSs and L2 learners.

Our recent study (Parshina, Laurinavichyute, & Sekerina, 2021), in which we investigated conventional eye-tracking measures of reading in Cyrillic by adult HSs and L2 learners of Russian who live in the United States, confirmed these predictions. We compared the eye movements of bilinguals with those observed in monolingual 8-year-old children (Korneev, Matveeva, & Akhutina, 2017) and adults (Laurinavichyute, Sekerina, Alexeeva, Bagdasaryan, & Kliegl, 2019). We found that HSs exhibited quantitatively different eye movement characteristics (i.e., longer mean fixation durations and lower probability of skipping words, but higher rates of regressions and multiple fixations on words). High-proficiency HSs resembled monolingual children the most, whereas low-proficiency HSs were at a disadvantage and read on a par with unbalanced L2 learners, suggesting that early exposure to the heritage language alone did not necessarily facilitate literacy acquisition.

The Present Study

In the present study, we took a step further from Parshina et al. (2021) by using the scanpath approach to investigate qualitative differences and similarities in global eye movement patterns among the four groups of Russian speakers (as opposed to the quantitative evaluation of word-level eye-tracking measures in Parshina et al.'s study). Although these groups were the same as in Parshina et al.'s study, to be able to compare the qualitative characteristics of the global eye movement patterns between groups, it was critical that all participants read the same sentences (they had read a different set of sentences in the previous study). To that end, although the current analysis includes some reanalyzed data (see the Method section for details), we also collected a large set of new data to include HSs of various proficiency levels and monolingual adults in the present study.

We had three goals in this study. The first was to identify scanpath patterns reflecting the scanpath reading processes that are common among Russian readers regardless of the speaker's group membership (i.e., monolinguals, children, L2 learners, HSs). Accordingly, our second goal was to investigate whether group membership would predict whether the reader would engage in a specific scanpath reading process. Based on our previous findings, we expected monolingual adults to engage in qualitatively different scanpath reading processes from the other three groups of readers. For HSs, we expected that high-proficiency HS readers would exhibit scanpath reading processes that are similar to those of children, and that low-proficiency HS readers would engage in the same process as low-proficiency L2 learners. Our third goal was specific to bilingual readers: to uncover the effects of various demographic and reading performance factors (e.g., age of arrival to the United States, exposure to the nondominant language, comprehension abilities, reading fluency) on scanpath reading processes, as such factors had been identified as strong predictors of reading performance in previous research (for a review, see Koda, 2005, 2007).

We capitalized on the fact that there are many young adults in New York City, New York (where we collected our data), who are either HSs of Russian or are learning Russian as L2s, so we asked participants to read simple, unambiguous Russian sentences of the type that are appropriate for monolingual children who are learning to read in Russian. Despite the simplicity of the materials in this study, the difference in scripts (Cyrillic vs. Latin) and the morphological principle of Russian orthography present some additional challenges for literacy acquisition in Russian for bilingual readers, beyond the typical difficulties associated with learning a L2 (i.e., vocabulary, grammatical knowledge).

Although the Russian orthography is characterized as shallow, with almost one-to-one correspondence between graphemes and phonemes, there are some irregularities. For example, the vowel position in a word dictates its pronunciation, which is not directly reflected in the orthography (e.g., the phoneme /o/ has multiple allophones, e.g., [o] and [ə], depending on the stress in the word). Another example is consonant assimilation, in which the pronunciation of a consonant depends on the position of the letter in the word (e.g., *lodka* is pronounced as [lótkə]), as well as the quality of the preceding or following sounds. Such discrepancies between pronunciation and spelling are due to the morphological principle of Russian orthography: The spellings of the morphemes stay invariant regardless of the phonological laws used in speech. This phenomenon requires readers to have both morphological awareness and knowledge of orthographic patterns. Typically, to avoid delays in literacy development, Russian children as early as those in second grade receive instruction in the morphemic analyses of words (Kerek & Niemi, 2012) and master decoding skills by fourth grade (Rakhlin, Kornilov, & Grigorenko, 2017). The situation, of course, looks quite different for adult HSs, who typically do not receive formal instruction in reading and writing in their heritage language and, as with L2 learners, struggle with the differences in scripts between their two languages.

Method

Participants

There were 120 participants distributed across four groups: 30 monolingual Russian-speaking adults (13 women; M_{age} = 23.3 years, range = 19–28), 30 monolingual Russian-speaking second graders (11 girls; M_{age} = 8.5 years, range = 8–9), 30 English-dominant HSs of Russian (14 women; M_{age} = 17.5 years, range = 13–24; $M_{age\_of\_arrival}$ = 4.3 years), and 30 English-dominant L2 learners of Russian (21 women; M_{age} = 21.2 years, range = 16–43). The data for 17 HSs and all the L2 learners (*n* = 30) came from Parshina et al. (2021) and were reanalyzed for the present study, using the scanpath approach. The rest of the data were new, namely, 30 monolingual speakers and 13 high-proficiency HSs. We also collected new data for the children (*n* = 30) to rule out general difficulties in reading and other cognitive processing abilities. To achieve this, we assessed the children's reading ability using the Standardized Assessment of Reading Skills (Kornev, 1997), as well their nonverbal fluid intelligence via the Raven's Colored Progressive Matrices (Raven, 2004), before the corpus-reading task.

Participants were recruited from three sites: an urban university in New York City (HSs and L2 learners) and a public school and a university in Moscow, Russia (children and monolingual adults, respectively). None of the HSs in this or the previous study (Parshina et al., 2021) had more than four weeks of formal instruction in Russian. All monolingual adult participants were skilled readers of Russian (i.e., university undergraduates), reported Russian as their native language, and did not identify as speaking any other language fluently. Before the start of the study, all participants over 18 years old and the parents of the children signed an informed consent or assent form (for minor participants under 18 years old) and filled out a language background questionnaire, administered in English or Russian (see Table 1 for the bilingual participants' characteristics).

Design and Materials

Reading Assessments

HSs often vary considerably in their heritage-language reading ability because of different extents of reading exposure. As noted earlier, because it is a highly influential factor, it is necessary to consider the proficiency level of bilingual speakers when conducting any kind of analysis. Operationally, we defined proficiency in bilingual reading in Russian as a set of scores on the Russian Oral Reading Fluency (ORF–Rus) test. In this task, participants read aloud the short text "Kak ja lovil rakov" (How I Was Catching Crayfish; 202 words; Kornev, 1997). The text is intended for monolingual Russian primary school students and measures the speed and quality of reading, as well as comprehension in Russian (not included in the final score calculation). The sentences in the text include a wide range of grammatical constructions in Russian (e.g., relative clauses, passives, null object), tenses, and different types of word order (subject–verb–object [SVO], VSO, OVS) and contain words of different frequencies.

Next, for the bilingual participants, we administered a parallel standardized English task, English Oral Reading Fluency (ORF–Eng) from the Woodcock Reading Mastery Tests third edition (Woodcock, 2011), to rule out general reading difficulties in the dominant language. The participants were asked to read aloud a short text (217

TABLE 1
Demographic and Performance Characteristics of the Two Bilingual Groups

Participant characteristic	Heritage-language speakers *M* (*SD*)	Second-language learners *M* (*SD*)
Number of participants	30	30
Age of arrival to the United States (years)	4.3 (5.4)	0.13 (0.75)
Daily Russian exposure (%)	25.6 (18.9)	7.9 (7.4)
Self-estimated comprehension (1–5)	3.2 (1.1)	2.8 (0.87)
Oral reading fluency: Russian	12.3 (6.0)	8.3 (2.7)
Oral reading fluency: English	26.6 (6.3)	28.1 (5.3)

words), in which sentences gradually increase in complexity, in English. The performance on both the ORF–Rus and ORF–Eng tests was scored on the basis of the formula for calculating the final score in the ORF–Eng test provided in the Woodcock Reading Mastery Tests manual. This formula includes such factors as total reading time, number of words in the passage, and number of errors (omissions, mispronunciations, word substitutions, hesitations, repetitions, and transpositions). Table 1 provides the oral fluency scores in both Russian and English.

All monolingual adult participants were classified as fluent in reading in Russian, based on the following: Their performance on the ORF–Rus test was at ceiling for all participants, Russian was their native language, and none of them were bilingual according to the language background questionnaire.

Data for Scanpath Analysis

The materials were 30 sentences from the children's version of the Russian Sentence Corpus (Korneev et al., 2017), appropriate for 8-year-old monolingual Russian-speaking children, as illustrated in examples 1 and 2:

Example 1						
Stimulus item	В магазине	Андрей	купил	молоко,	сметану,	творог.
Transliteration	v magazine	Andrei	kupil	moloko	smetanu	tvorog
Gloss	in store	Andrei	bought	milk	sour cream	cottage cheese
Translation	In the store Andrei bought milk, sour cream, cottage cheese.					
Example 2						
Stimulus item	Недалеко	был сложен	стог сена,	рядом	стояли	грабли.
Transliteration	nedaleko	byl slozhen	stog sena	ryadom	stoyali	grabli
Gloss	nearby	was stacked	haystack	next to	stood	rake
Translation	A haystack was stacked nearby, a rake was next to it.					

The sentences were presented to participants in isolation for silent reading and represented diverse types of grammatical structures typical of the Russian language (e.g., canonical and noncanonical word orders, passive and active voice constructions, sentences with null subjects, relative clauses). All words in the text corpus were annotated for length and frequency (Lyashevskaya & Sharov, 2009). Table 2 presents the descriptive characteristics of all the corpus words and sentences.

TABLE 2
Descriptive Characteristics of the Child Russian Sentence Corpus

Corpus characteristic	Child Russian Sentence Corpus
Number of sentences	30
Number of words	227
Sentence length (words)	*M* = 8, range = 6–9
Word length (letters)	*M* = 5.6, median = 6, range = 1–13
Word frequency (items per million)	*M* = 3,088.2, median = 2,583.3, range = 7.4–7,537.7

Procedure

All sentences were presented in black, 22-point Ubuntu Mono Normal font on a light gray background programmed in Experiment Builder (SR Research Ltd.). We used a BenQ XL2411Z 144 Hz monitor (resolution: 1920 × 1080 pix) controlled by a ThinkStation computer. Eye movements were recorded using an EyeLink 1000 Plus desktop mount eye tracker with a chin rest. The right eye was tracked, at 1000 Hz rate.

The experiment started with a 9-point calibration procedure repeated after every 15 sentences. Stimuli appeared on the screen in randomized order. Each sentence was followed by a multiple-choice question to ensure that the participant was paying attention and reading for comprehension. For example, the sentence in example 1 was followed by the question "What did Andrei buy in the store?" with "bread" and "milk" as possible answers.

Sentence presentation was as follows. We began by performing drift correction, for which the participant fixated on a black dot at the left edge of the screen. The dot disappeared after it had been fixated for 500 ms, followed by the presentation of the sentence in which the first letter of the first word appeared in the position of the black dot. After reading the sentence, the participant looked at a red dot in the lower right-hand corner of the screen. After 500 ms, the multiple-choice question appeared. As soon as the participant clicked on one of the options, the presentation of the next sentence began with the drift correction. Overall, participants took approximately 30 minutes to complete the task, ranging from

10 minutes for monolingual adult and child participants to 40 minutes for low-proficiency bilinguals.

Data Analysis

The first stage of our analysis served to identify the scanpath reading processes occurring in our data set. It consisted of the following steps:

1. Plotting the scanpaths for each sentence and participant for visual inspection
2. Calculating the pairwise scanpath dissimilarity scores for each sentence
3. Fitting a map of the scanpaths for each sentence (multidimensional scaling)
4. Conducting cluster analysis for each sentence using the map as the input
5. Identifying a prototypical reading process of each detected cluster

In the second stage, we investigated the factors that predict which of the scanpath reading processes a participant adopted for a given sentence. The materials and the script used for the analyses reported below, as well as all supplemental materials, are available on the Open Science Framework project page (https://osf.io/9z7yv/).

The overall comprehension accuracy was high, at 91% (SD = 28%). Average accuracy in answering the comprehension questions was almost at ceiling for three out of the four groups: 95% for the monolingual adults (SD = 21%), 99% for the monolingual children (SD = 10%), and 91% for the HSs (SD = 29%). The L2 learners' accuracy was the lowest, at 85% (SD = 36%). Only sentences with correct answers to the comprehension questions were included in the scanpath analysis.

Plotting Scanpaths for Each Sentence and Participant

First, to get a general idea of how participants read the sentences, we created plots of the scanpaths for every participant and every sentence by using the x-coordinate of each fixation and its time within the trial (the fixations on y-coordinates remained largely constant because the sentences were presented without line breaks). Figure 1 shows the scanpaths recorded for example 1, which was the sentence that elicited the least diverse scanpaths (participants generally read it in a similar way, according to the scanpath similarity measure by von der Malsburg & Vasishth, 2011). Each plot shows the scanpath for one participant (with the participant number at the top, coded by color: ML1–30 are the 30 monolinguals, CH1–30 are the 30 children, HS1–30 are the 30 HSs, and L21–30 are the 30 L2 learners). The x-axis shows the words, and the y-axis indicates the trial time in seconds (for the scanpath plots for all the sentences, see file S1 in the supplemental materials).

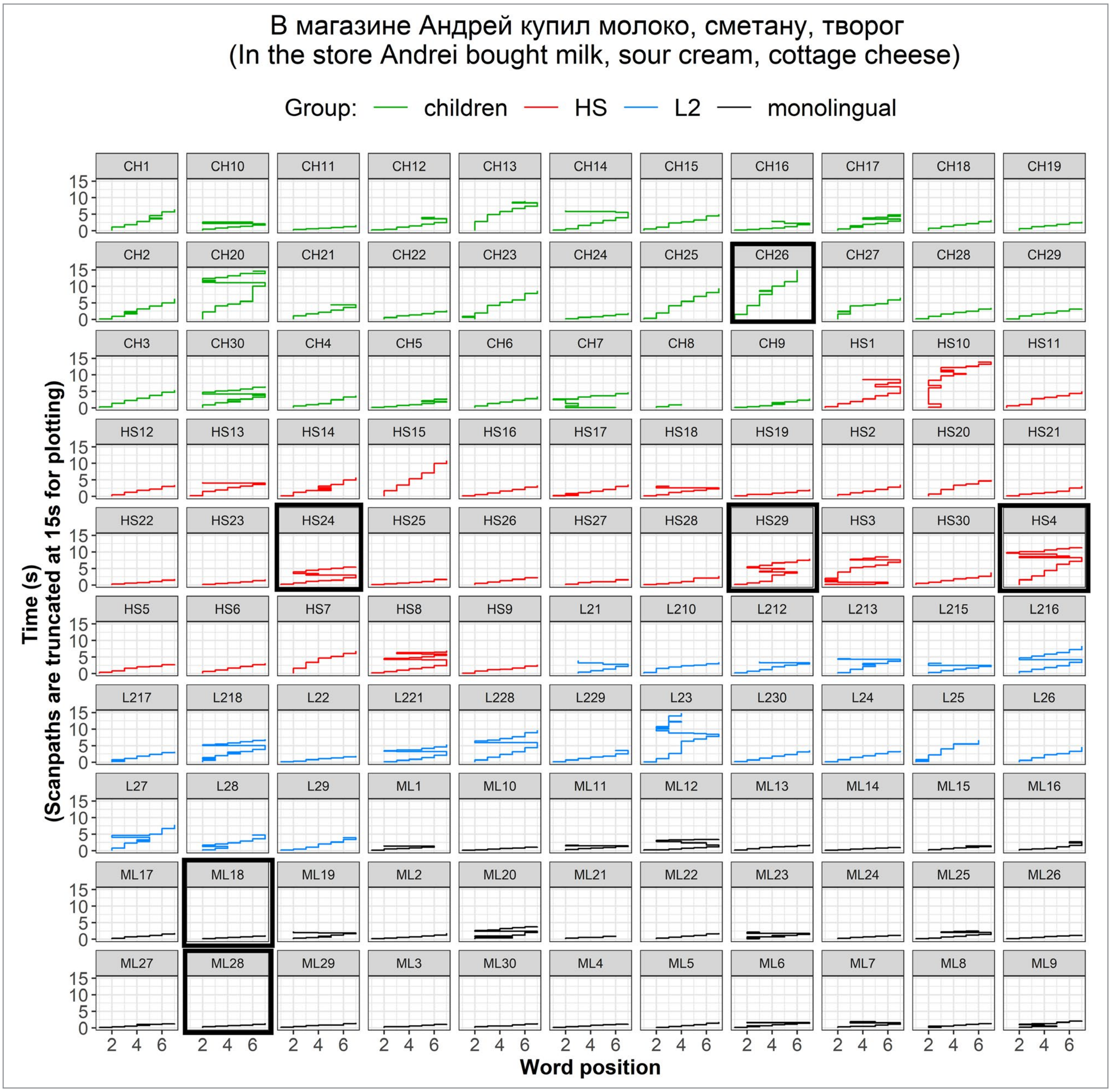
Visual inspection of Figure 1 reveals that some participants read slower (i.e., the scanpath line is extended vertically; e.g., CH26, HS4), made more regressions (i.e., the scanpath line returns to the previous words in the sentence; e.g., HS24, HS29), or skipped words more often (i.e., scanpath line is flat across three or more words; e.g., ML18, ML28) than others. Figure 2 depicts the scanpaths for example 2, which elicited the most variable gaze patterns, and shows that the scanpaths vary in their characteristics from participant to participant: Some participants skipped a lot (e.g., ML26) or read slowly but without skipping or long regressions (e.g., CH18), and other participants read very slowly and produced many regressions (HS8, ML17), or reread longer passages (e.g., CH30, L24).

Calculating the Scanpath Dissimilarity Scores

Next, for each sentence, we calculated the pairwise dissimilarities of all the scanpaths. This measure calculates the difference between two scanpaths as a function of the spatio-temporal differences between their matched (i.e., sequentially aligned) fixations, where the x- and y-coordinates and durations of the fixations are represented as continuous variables (for a detailed description of the dissimilarity measure, see von der Malsburg & Vasishth, 2011). For example, if two matched fixations have the same x- and y-coordinates, then their dissimilarity is equal to the difference in their durations. In contrast, if two matched fixations are far away from each other, the difference between them is the sum of their durations. The rationale for that is the following: If these two fixations are long, it means that the spatial disparity between them lasted longer (readers looked at different things longer) and, therefore, these two fixations add more dissimilarity than two fixations with short durations. When the distance between two matched fixations is in the medium range (neither too far nor too close), the dissimilarity score is a weighted sum of the difference and the sum of the fixation durations. We calculated the scanpath dissimilarity scores using the scanpath software package for R (von der Malsburg et al., 2015). Having obtained the dissimilarity scores for each pair of scanpaths recorded for a sentence, we then calculated the average dissimilarity among the scanpaths for each sentence and determined which sentences had elicited the most and which the least diverse scanpaths in the corpus.

This difference in scanpath variability between examples 1 and 2 is to be expected in light of their syntactic and semantic characteristics. Example 1 (see Figure 1) has a canonical SVO word order and includes high-frequency words (M_{freq} = 4250 ipm). In contrast, example 2 (see Figure 2) has a noncanonical OVS word order, passive voice, and words of lower frequency (M_{freq} = 407 ipm). Therefore, in comparison with example 1, participants fixated

FIGURE 1
Scanpaths for Example 1 With the Least Diverse Scanpaths



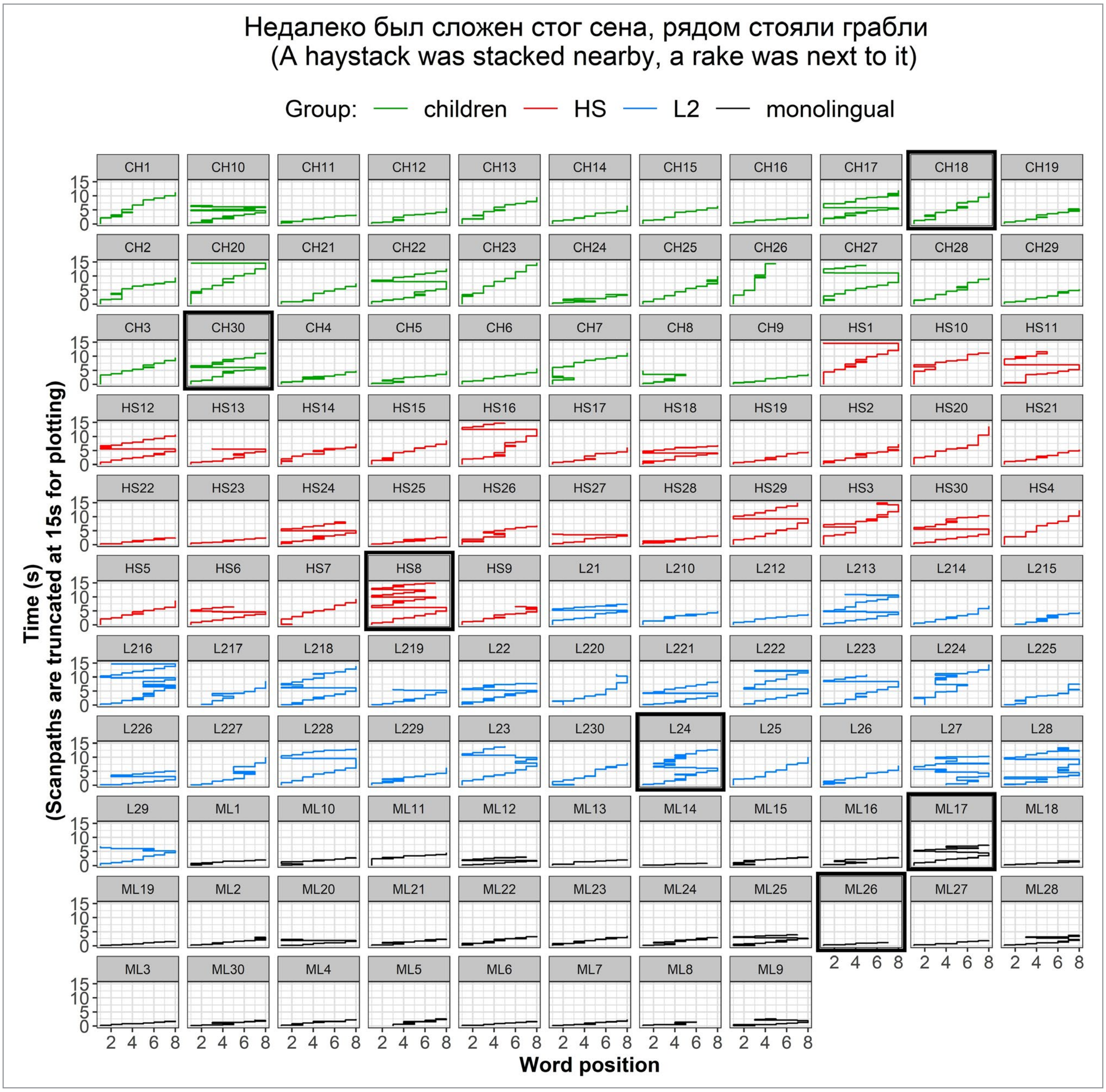
Note. The participant number is at the top of each cell, coded by color: ML1–30 are the 30 monolinguals, CH1–30 are the 30 children, HS1–30 are the 30 heritage-language speakers, and L21–30 are the 30 second-language learners. Scanpath plots referred to in the text are framed. Scanpaths are truncated at 15 s for readability of the plots. The color figure can be viewed in the online version of this article at http://ila.onlinelibrary.wiley.com.

the words more (e.g., CH18, ML17) and reread them (e.g., L24) and the entire sentence (e.g., CH30, HS8, L24) multiple times in example 2.

Fitting Maps of Scanpaths

Next, to visualize the variability of the scanpaths across all the corpus sentences, we used multidimensional scaling (Kruskal, 1964) to calculate a map of the scanpaths for every sentence (see Figure 3). In these maps, every scanpath (one from each participant) is represented as a point (e.g., triangles for monolinguals). Similar scanpaths are located closer to each other (i.e., the participants read in the same way; see Figure 3A). The farther away the scanpath is from the gravity center of the map, the more unusual or irregular was the reading pattern as compared with those of the other participants (see Figure 3B). More difficult sentences typically elicit more variable, and hence irregular,

FIGURE 2
Scanpaths for Example 2 With the Most Diverse Scanpaths



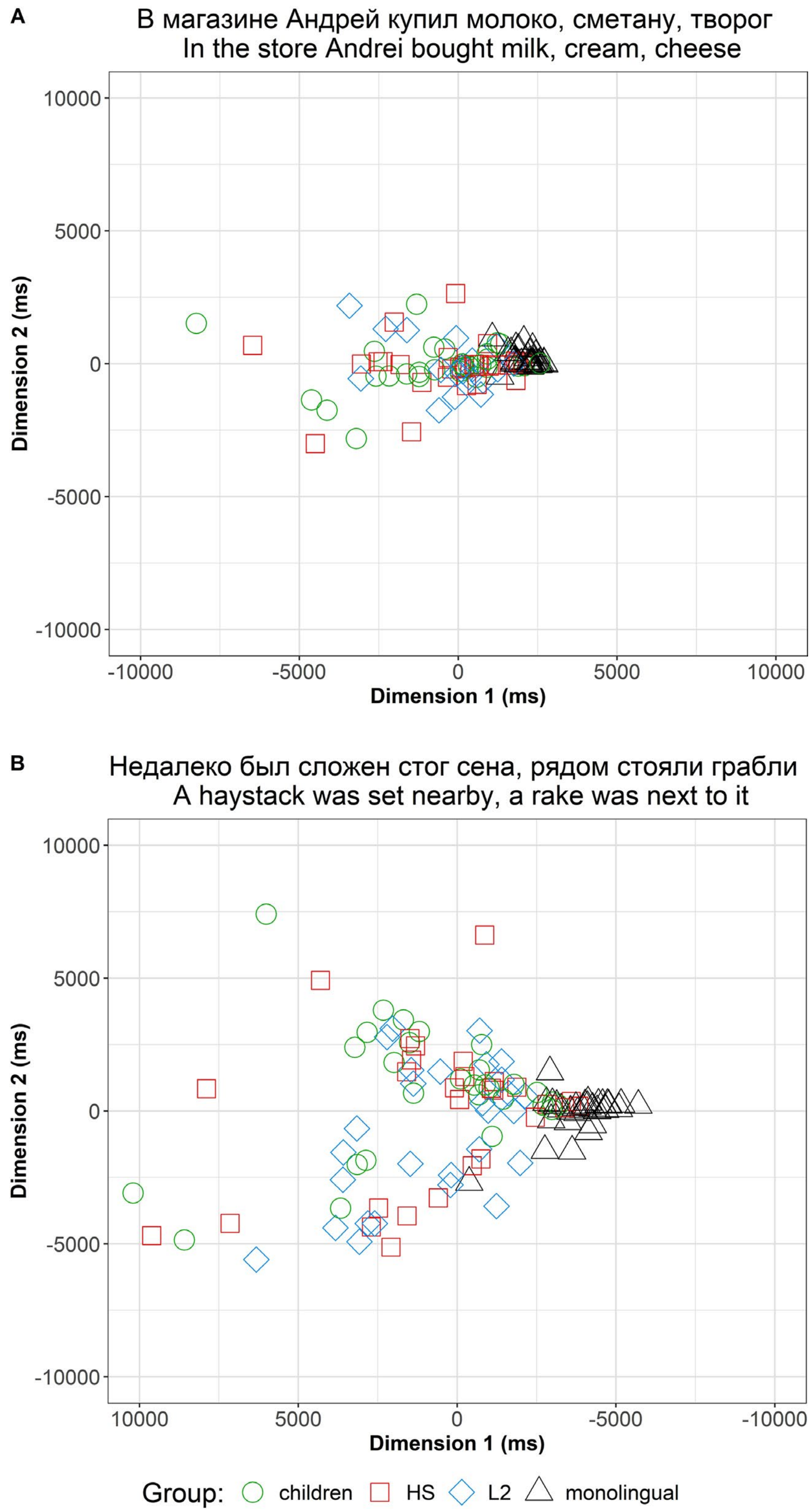
Note. The participant number is at the top of each cell, coded by color: ML1–30 are the 30 monolinguals, CH1–30 are the 30 children, HS1–30 are the 30 heritage-language speakers, and L21–30 are the 30 second-language learners. Scanpath plots referred to in the text are framed. Scanpaths are truncated at 15 s for readability of the plots. The color figure can be viewed in the online version of this article at http://ila.onlinelibrary.wiley.com.

scanpaths (cf. Figure 3A for example 1 with Figure 3B for example 2; see also von der Malsburg et al., 2015).

The goodness of fit of a map depends on the number of its dimensions (for more detailed specification of the procedure for fitting maps, see von der Malsburg et al., 2015; von der Malsburg & Vasishth, 2011, 2013). A large number of dimensions results in a map with more degrees of freedom and a smaller percentage of variability that cannot be explained by the map. Therefore, high-dimensional maps more faithfully represent the similarities among the scanpaths; however, they also risk overfitting the data. The number of dimensions in our maps was therefore set to 6, such that the percentage of unexplained variance by the maps was, on average, 11% (*SD* = 1.17%), which indicates a reasonably good fit (Kruskal, 1964). Maps of scanpaths were fitted using the isoMDS function in the

FIGURE 3

Maps of Scanpaths Showing the Two Dimensions Explaining Most of the Scanpath Variance: (A) The Map for Example 1, Which Elicited the Smallest Scanpath variance; and (B) the Map for Example 2 With the Most Varied Scanpath Patterns



Note. The color figure can be viewed in the online version of this article at http://ila.onlinelibrary.wiley.com.

R package MASS (Venables & Ripley, 2002). (See Figure S2 in the supplemental materials for the scanpath maps for all the sentences.)

The map dimensions can correspond to interpretable scanpath features. For instance, examining Figure 2 suggests that dimension 1 in Figure 3B corresponds to the variability in reading speed, whereas dimension 2 represents the amount of rereading. For other sentences, the dimensions can capture different aspects of the scanpath variance. Thus, hypotheses tests are needed to investigate which features dominate the structure of a given scanpath space.

Cluster Analyses for Each Sentence

Our goal in the cluster analysis was to identify the categories of scanpaths that represent qualitatively different scanpath reading processes, if any. We identified the clusters for each sentence by applying Gaussian mixture modeling (using the mclust package for R; Fraley & Raftery, 2007), where all the parameters of the clusters (e.g., position, variance, rotation) were allowed to vary freely. The benefit of using Gaussian mixture modeling is the ability of the procedure to detect clusters even if they overlap (vs. *k*-means clustering) based on the distributional properties of the data. Models were fitted for numbers of Gaussians fixed at 3 to avoid overfitting the data (i.e., capturing random variation in reading patterns) and to prevent clusters that capture the tails of slightly non-Gaussian distributions. (See Figure S3 in the supplemental materials for maps of the scanpath clusters for all the sentences.)

We can overlay the derived clusters directly onto the participants' scanpaths to obtain a general idea of which features are characteristic of a cluster (e.g., reading times, regressions, skipping, number of reading passes). Figure 4 presents the scanpaths for example 2, color-coded by cluster. Cluster 1 (magenta) includes scanpaths that are close to the baseline as characterized by regular left-to-right reading, short fixations, frequent word skipping, and few regressions. Cluster 2 (brown) is also characterized by regular left-to-right reading but has increased fixation durations, backward saccades to reread individual words, some sentence rereading, and instances of word skipping. Finally, cluster 3 (blue) is characterized by considerably increased reading times, virtually no word skipping, and frequent rereading of the sentence, occasionally multiple times.

Identifying Prototypical Scanpath Reading Processes

Finally, we identified the prototypical scanpath reading process for each cluster represented by the scanpath closest to each cluster's center of gravity. In other words, in each sentence and each cluster within that sentence, we identified the scanpath with the shortest distance to the center of the respective cluster (using the map of clusters for distance calculations; see Figure S3 in the supplemental materials). As a result, we were able to identify three prototypical scanpath reading processes adopted by Russian readers: a fluent scanpath reading process (cluster 1), an intermediate scanpath reading process (cluster 2), and a beginner scanpath reading process (cluster 3). Figure 5 presents these three scanpath reading processes for example 2. (See Figure S4 in the supplemental materials for the prototypical scanpath reading processes for all the sentences.) Note that at this point, these processes are descriptive in nature. As can be seen in Figure 3, there is a continuum of scanpaths, and the clusters identified in the cluster analysis serve to concisely characterize and summarize that continuum. Across all 30 sentences in the corpus, our participants were classified as follows: 27.2% (*SD* = 4.8%) exhibited the fluent scanpath reading process, 49.3% (*SD* = 6.1%) preferred the intermediate scanpath reading process, and 23.5% (*SD* = 7.2%) predominantly followed the beginner scanpath reading process.

Results

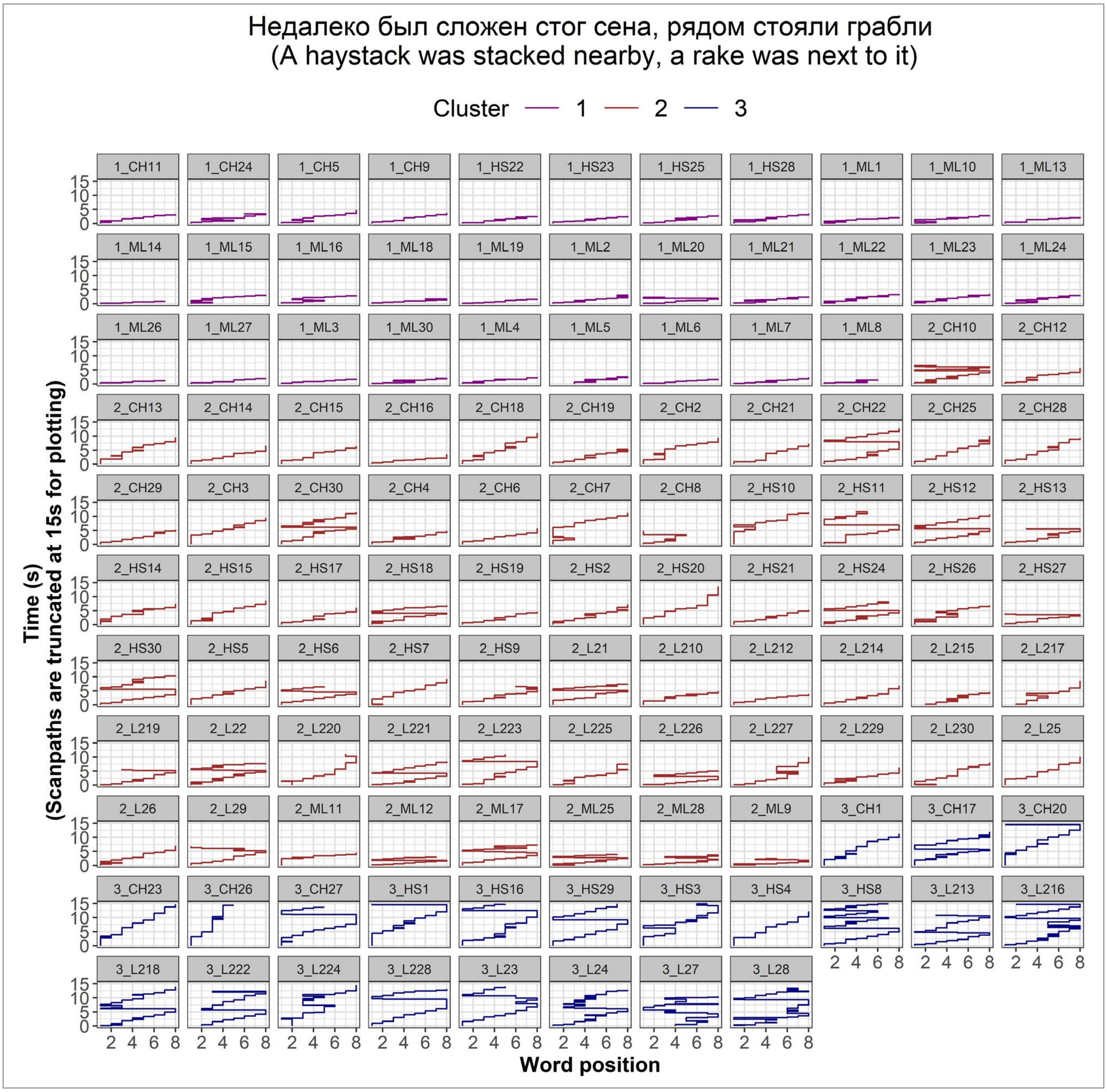
Recall that our study had three goals: (1) to identify scanpath patterns reflecting scanpath reading processes that are common among Russian readers regardless of the speaker's group membership, (2) to investigate whether group membership would predict engagement in a specific scanpath reading process, and (3) specific to bilingual readers, to uncover the effects of various demographic and reading performance factors on scanpath reading processes.

Common Scanpath Reading Processes

All data analyses were performed in R (version 3.5.1; R Core Team, 2018). For the generalized linear mixed models, we used lme4 (1.1-13) and sjPlot package 2.8.3 (for data visualization and the computation of *p*-values; Lüdecke, 2017). Throughout the analysis, all generalized linear mixed models included random intercepts for sentences and readers.

Table 3 (top panel) presents the means and standard deviations for some canonical eye movement measures for each of the three scanpath reading processes. All *p*-values for differences between scanpath processes (as assessed using series of linear mixed-effect models that included process as a fixed predictor and eye movement measure as an outcome) were less than .001 (see Table A1 in Appendix A for estimates and corresponding *p*-values). Table 3 (bottom panel) presents the percentage distribution of the 120 participants for each of the scanpath reading processes across all 30 sentences (i.e., the distribution of groups in each scanpath reading process, together, comprise 100%).

FIGURE 4
Sample of the Scanpaths Coded by Clusters for Example 2, Which Elicited the Most Diverse Eye Movement Patterns



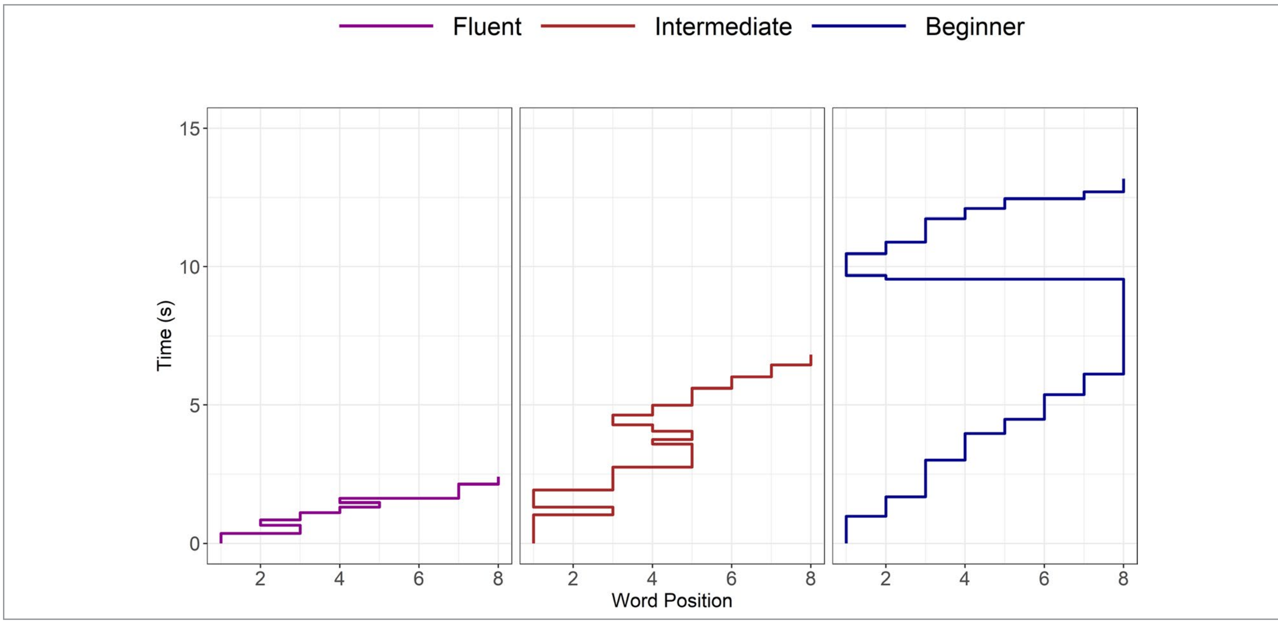
Note. The cluster number is at the top of each cell, followed by the participant number. The participants are coded by color: ML1–30 are the 30 monolinguals, CH1–30 are the 30 children, HS1–30 are the 30 heritage-language speakers, and L21–30 are the 30 second-language learners. Scanpath plots are truncated at 15 s for plotting. The color figure can be viewed in the online version of this article at http://ila.onlinelibrary.wiley.com.

Although all three scanpath reading processes were found in all four groups of Russian readers, Table 3 (bottom panel) reveals that for each process, there was a group that used this process most frequently. Figure 6 shows the counts of instances of scanpath reading processes that each reader contributed. For every scanpath reading process, there were readers who showed a strong preference for it. Some readers did not use the fluent or beginner processes at all, but the intermediate scanpath reading process was found in most participants with the exception of five monolingual readers.

Group Preferences for Scanpath Reading Processes

After we determined the three scanpath reading processes common in all four groups, we investigated the question of

FIGURE 5
Prototypical Scanpath Reading Processes in Example 2 as Identified by the Scanpaths Closest to the Centroids of the Clusters



Note. The color figure can be viewed in the online version of this article at http://ila.onlinelibrary.wiley.com.

TABLE 3
Means and Standard Deviations for the Eye Movement Measures (Top Panel) and Percentage Distribution of the Participants Composing Each of the Scanpath Reading Processes

	Scanpath reading process		
Measure	Fluent *M* (*SD*)	Intermediate *M* (*SD*)	Beginner *M* (*SD*)
Gaze duration (ms)	289.3 (81.8)	689.9 (338.2)	1,053.5 (544.4)
Skipping rate (%)	17.1 (13.7)	8.7 (11.9)	5.8 (10.9)
Fixation count/word	1.3 (0.390)	2.8 (1.1)	5.1 (2.1)
Regression rate (%)	12.9 (14.7)	25.4 (18.7)	38.2 (22.7)
Count of word readings	1.0 (0.270)	1.4 (0.492)	2.2 (0.923)
Total time reading/sentence (s)	2.1 (0.761)	6.4 (2.9)	13.8 (5.9)
Monolinguals	73.6% (4.8%)	10.0% (3.4%)	0.5% (0.34%)
Children	11.0% (2.2%)	35.7% (2.8%)	22.1% (3.1%)
Heritage-language speakers	12.2% (2.0%)	28.8% (2.9%)	35.1% (3.1%)
Second-language learners	3.3% (0.96%)	25.5% (3.8%)	42.3% (4.3%)

which group (i.e., monolingual adults, children, HSs, L2 learners) was characterized by which preferred process. We predicted that monolinguals would mostly adopt the fluent scanpath reading process and that children's and HSs' scanpath reading processes would overlap. We also predicted that proficiency would have an effect, in that low-proficiency HSs would be clustered together with the L2 learners.

To test these predictions, we ran a binomial mixed-effects model for each of the three scanpath reading processes (0 = *scanpath does not belong to the process*; 1 = *scanpath belongs to the process*) and for each group where group membership was dummy-coded as a binary variable (0 = *participant is not a group member*; 1 = *participant is a group member*). Thus, the model estimates the probability of a participant in a specific group to exhibit a particular scanpath reading process when compared with all other readers not belonging to the same group. We calculated the effect sizes (Cohen's *d*) using the lme.dscore function from the EMAtools package for R (Kleiman, 2017; see the R code example in Appendix B).

FIGURE 6
Individual Differences in the Scanpath Reading Processes

Note. The graph shows how many instances of the scanpath reading process each participant produced. The participant number is at the top of each cell, coded by color: ML1–30 are the 30 monolinguals, CH1–30 are the 30 children, HS1–30 are the 30 heritage-language speakers, and L21–30 are the 30 second-language learners. The color figure can be viewed in the online version of this article at http://ila.onlinelibrary.wiley.com.

The results of the generalized linear mixed modeling are presented in Table 4 ($N_{participants}$ = 120, $N_{sentences}$ = 30, observations = 3,477). They indicate that in comparison with other readers, monolingual speakers exhibited a high probability of adopting the fluent scanpath reading process. Accordingly, it was highly unlikely that monolinguals would rely on the intermediate or beginner processes. Monolingual children read sentences by following the intermediate process more often than other readers did. HSs did not show a strong preference for either the intermediate or beginner scanpath reading process, whereas, out of all the groups, L2 learners had the highest probability of engaging in the beginner scanpath reading process, although they also produced many scanpaths in the intermediate category.

Demographic and Reading Performance Factors in Bilingual Readers

For each of the two groups of bilingual readers, we tested the impact of two demographic factors on their reading processes—age of arrival to the United States and daily exposure to Russian—in addition to two reading performance factors—self-estimated comprehension ability in Russian and proficiency in reading (as defined by the ORF–Rus test)—along with their scores on the ORF–Eng. Two predictors in the model were statistically significant (see Tables A2 and A3 in Appendix A for the full statistical analysis and see Appendix B for the R code example).

First, what matters for HSs ($N_{participants}$ = 30, $N_{sentences}$ = 30, observations = 896) in engaging in one of the three processes was their proficiency level in reading in Russian (ORF–Rus). Higher proficiency led to a reliance on fluent reading ($\beta = 2.6$, standard error [SE] = 0.57, $d = 1.6$, $p < .001$), whereas lower proficiency resulted in a beginner scanpath reading process ($\beta = -1.5$, $SE = 0.41$, $d = -1.2$, $p < .001$). For L2 learners ($N_{participants}$ = 30, $N_{sentences}$ = 30, observations = 814), the probability of engaging in the fluent scanpath reading process increased with higher self-estimated comprehension scores ($\beta = 2.0$, $SE = 0.73$, $d = 0.71$, $p = .018$).

Discussion

In this study, we applied a scanpath approach to establish and define global eye movement patterns that compose the scanpath reading processes in bilingual and monolingual speakers of Russian. The cluster analysis that grouped similar gaze trajectories in the reading of 30 sentences allowed us to identify three such processes based on their distinct scanpath patterns: fluent, intermediate, and beginner (see Table 5 for the conceptual comparison of the eye movement characteristics of these processes). We also found that the group membership of the participants (monolingual adults, children, HSs, and L2 learners) strongly correlated with the clustering of their gaze trajectories into one or another common scanpath reading process. Finally, we established that out of the demographic and reading performance factors that represented individual differences in the bilingual readers, only proficiency (for HSs) and comprehension scores (for L2 learners) affected which scanpath reading process they adopted.

TABLE 5
Conceptual Comparison of the Three Scanpath Reading Processes[a]

Measure	Fluent	Intermediate	Beginner
Fixation duration (ms)	289	690	1,054
Word skipping	17%	9%	6%
Total reading time (ms)	2	6	14
Short leftward saccades	Few	✓	✓
Long regressions	Few	✓	✓
Sentence rereadings		Few	✓

[a]Matching the descriptive characteristics in Table 3 and the statistical analysis in Table A1.

TABLE 4
Parameter Estimates for Generalized Linear Mixed Models: Probability of Engaging in One of the Three Scanpath Reading Processes by Group

	Scanpath reading process											
	Fluent				Intermediate				Beginner			
Group	Est.	*SE*	*p*	*d*	Est.	*SE*	*p*	*d*	Est.	*SE*	*p*	*d*
Monolingual	6.8	0.63	**<.001**	3.1	−2.5	0.36	**<.001**	−1.3	−6.3	0.90	**<.001**	−1.0
Children	−2.4	1.1	.069	−0.51	1.6	0.39	**<.001**	0.74	0.15	0.67	1	−0.13
Heritage-language speakers	−3.3	1.1	**.006**	−0.47	0.54	0.41	.579	0.22	1.4	0.65	.081	0.32
Second-language learners	−4.6	0.96	**<.001**	−0.78	0.41	0.42	.972	0.16	2.7	0.61	**<.001**	0.77

Note. Est. = estimate; *SE* = standard error. The cells with estimates in which there is a statistically significant effect are in boldface. Bonferroni correction applied.

The fluent scanpath reading process is characterized by straight left-to-right reading that includes short fixation durations, a high word-skipping probability, and an absence of long regressions and sentence rereadings. We suggest that this process is a characteristic of participants who generally do not experience any difficulties in lexical access or morphosyntactic processing in reading (e.g., monolingual adults) while comprehending simple Russian sentences.

The primary characteristics of the intermediate scanpath reading process are fixation durations that are twice as long, higher rates of producing short leftward saccades, a lower probability of word skipping, and an absence of sentence rereadings. Previous studies have suggested that short regressions to the beginning of the current or previous word (i.e., word rereading) can be the result of the reader's need to perform a local targeted repair, namely, to come back to the area where the processing difficulty occurred (e.g., Frazier & Rayner, 1982; Meseguer et al., 2002). Although our sentences did not include experimentally created ambiguities, we propose that short leftward regressions serve the same function, as they help resolve local and lower level processing difficulties, such as word recognition failure (Bicknell & Levy, 2011). The natural tendency of readers to avoid such failures also triggers a careful reading pattern, which is characterized by the absence of skipping and slower total reading times. This reading behavior might be optimal for readers who have insufficient exposure to the language (e.g., L2 learners; Gollan, Montoya, Cera, & Sandoval, 2008; Schmidtke & Moro, 2020; Whitford & Titone, 2012, 2016) or are unfamiliar with reading materials (e.g., children, adult poor readers; Barnes & Kim, 2016; Kuperman & Van Dyke, 2011).

Finally, the beginner scanpath reading process is characterized by the longest fixation durations, almost no word skipping, very long total reading times, and rereading of the whole sentence, sometimes multiple times. We suggest that this scanpath reading process characterizes readers who not only experience delays in visual word recognition but also struggle with global challenges in semantic and morphosyntactic information integration. These readers often reparse the sentence from scratch after the first-pass reading. Following von der Malsburg and Vasishth (2011, 2013) and the good-enough parsing account (Ferreira et al., 2002), it is possible that these readers have difficulties with incremental interpretation of the whole sentence during the first-pass reading. Instead, they assemble lexicosemantic information from individual words in a piecemeal fashion and only integrate it with the syntactic structure during the second or even third rereadings (evident through word skipping and faster reading times in the second and any subsequent rereadings).

The beginner scanpath reading process might be the most viable way to allocate limited cognitive resources (attention, working memory, and the decoding of visual information) and reduce cognitive load during written language comprehension, which is, undoubtedly, a challenging task for these readers (for a review on cognitive automaticity in L2 language processing, see Segalowitz & Hulstijn, 2009). We suggest that the beginner scanpath reading process is preferred for readers who are either at the very first stages of literacy acquisition (e.g., preschool children) or have just started to acquire a L2, especially if that language is dissimilar to the dominant language (e.g., phonology, grammar, orthography).

In general, our results confirm the predictions of the divergent attainment trajectory of heritage-language development (Benmamoun et al., 2013; Montrul, 2008; Polinsky & Scontras, 2020; Scontras et al., 2015) and findings from previous reading studies (Cop et al., 2015; Parshina et al., 2021). The scanpaths of monolingual speakers were consistent with the fluent scanpath reading process, whereas those of HSs depended on their proficiency. The higher the proficiency was, the higher the probability was that their gaze trajectories were more advanced, that is, similar to those of monolingual children, who showed a stronger tendency toward the intermediate scanpath reading process as compared with other readers (or in some cases, with those of monolingual adults who used the fluent scanpath reading process). Low-proficiency HSs, in contrast, read on a par with L2 learners of Russian, who engaged in the beginner scanpath reading process more often than any other group.

The absence of the effects of other demographic factors in HSs, besides proficiency (i.e., age of arrival to the United States, daily exposure to Russian), on their ability to move from the beginner to the intermediate scanpath reading process suggests that despite their early exposure to their heritage language in its spoken modality, their reading skills (as opposed to auditory comprehension, production, phonology, grammar, and vocabulary knowledge) do not seem to benefit from acquiring their heritage language in the family, at least not to the extent that it could be detected in the present study. These readers exhibited reading behaviors typical of unbalanced L2 learners who started to learn the L2 later in adulthood and in a classroom setting. This conclusion supports the previously reported results of there being no advantage for HSs in literacy acquisition (Ke, 1998; Xiao, 2006; Zhang & Koda, 2018).

Not surprisingly, the L2 participants showed the strongest reliance of any group on the beginner scanpath reading process. Very few of them produced scanpaths (3%) that followed the fluent scanpath reading process, and the ability to engage in it was predicted by their self-estimated comprehension scores. We hypothesize that L2 learners' engagement in the beginner scanpath reading process is due to the difficulties they experience with the grapheme-to-phoneme decoding process while reading in Russian (Comer, 2012; Comer & Murphy-Lee, 2004). The time that L2 learners spend on this process (which is automatized in more proficient readers) delays visual word recognition and makes information integration from the entire sentence challenging (Gor, 2017). As a result, L2 learners have to use a global-level remedy for comprehension difficulties (i.e., they reread the sentence multiple times). It is also likely that the cognitive resources allocated to reading in the L2 are limited by working memory. Thus, we hypothesize that the most distinct characteristic of the beginner scanpath reading process, the rereading of simple sentences, is a way to reallocate the resources and give the parser a fresh start after all initial difficulties have been resolved during the first-pass reading.

In contrast to HSs, it was not the proficiency but their self-estimated comprehension ability that was a statistically significant predictor of reading fluency for L2 learners. Specifically, higher comprehension scores predicted the ability of L2 learners to engage in the fluent scanpath reading process. We hypothesize that this finding might be explained by the good-enough parsing account (Ferreira et al., 2002) if one assumes that comprehension scores reflect the participants' estimation of their vocabulary size in Russian. Their vocabulary knowledge gives these readers an advantage in reading simple, child-friendly sentences, as the absence of ambiguities and straightforward syntax do not require a potential reanalysis of the sentences. The parser simply scans the words, extracts their meanings, and comes back to interpretation later, resulting in occasional instances of the fluent scanpath reading process while avoiding in-depth processing in reading.

To summarize, the scanpath approach that we adopted in this study draws a general picture of bilingual reading, wherein the difficulties that bilinguals experience with both visual word recognition and morphosyntactic and semantic information integration can be explicitly uncovered and visualized for professionals who work with bilingual speakers. Our findings provide additional support for the theories of bilingual word recognition (bilingual interactive activation plus: Dijkstra & van Heuven, 2002; multilink: Dijkstra et al., 2019): The language exposure (and, therefore, the proficiency of the readers and the subjective frequency of the words in the language) is critical for the efficiency of lexical access in bilingualism.

Furthermore, our scanpath analysis revealed that bilingual speakers vary in the way they engage in different types of scanpath reading processes. For some, rereading words, phrases, or clauses is the only way to build a whole-sentence representation. Such a process is more in line with retrieval interference theories, in which memory-based retrieval operations and individual differences are responsible for difficulties in bilingual language comprehension (Cunnings, 2017; Van Dyke et al., 2014). For others, faster reading without rereading is the most efficient approach; this is consistent with the theories that place lexical retrieval, semantics, and heuristics as the main tools bilinguals use to scaffold sentence meaning (shallow structure hypothesis: Clahsen & Felser, 2006; good-enough parsing account: Ferreira et al., 2002). Crucially, we saw that the choice of a scanpath reading process is not static, as bilingual readers occasionally switched from one process to another. Thus, successful language comprehension can be achieved in multiple ways by an individual, reflecting the importance of individual differences in literacy acquisition in bilingualism.

Limitations and Future Directions

There are some limitations of the study that should be addressed in future research. First and foremost, the three scanpath reading processes that we identified through cluster analysis are largely descriptive in nature. Although they represent concise summaries of the variability in gaze trajectories among different groups of Russian readers, more research is needed to clearly delineate the underlying mechanisms that drive written language comprehension. The fact that many readers in our study produced scanpaths that reflected multiple scanpath reading processes (e.g., the fluent scanpath reading process in example 1 but the intermediate scanpath reading process in example 2) and that there is considerable individual and group-level variation suggests that scanpath patterns may also be on a continuum.

The scanpath approach used in this investigation is one way to characterize this continuum. One question remains: Which underlying factors facilitate the transition of readers, be they monolingual or bilingual, adult learners or children, along the continuum, from the beginner scanpath reading process, to intermediate, to fluent? Specifically, future research should focus on (a) linguistic properties, that is, the lexical and structural effects of the materials on the scanpath reading process (e.g., the surprisal cost of a word in the sentence, word predictability, sentence complexity); and (b) the extralinguistic properties, that is, the effect of individual differences between participants that have previously been reported to impact the scanpath reading processes (e.g., working memory capacity, interference factors). Also related to the extralinguistic properties, future research should additionally consider the possibility of some variability in scanpath reading processes stemming from the cultural and/or instructional differences between the countries of the participants in our study (i.e., the United States, Russia): Will the international context or instructional method of literacy acquisition affect the reading processes?

A second important question for future research concerns the universal nature of scanpath reading processes and how they interact with the orthography for bilingual readers. In our study, bilingual readers read in the Cyrillic alphabet, which is different from the Roman-based alphabet of the dominant English. When HSs read in their weaker language that still shares the same script (e.g., Spanish, Italian, French) as the dominant language, would they benefit from the script similarities and move along the reading continuum faster, or even skip the beginner process completely? We speculate that although the quality of a given scanpath reading process(es) might stay the same (i.e., fluent, intermediate, beginner), the number of challenges in grapheme-to-phoneme conversion will be reduced, thus lowering the cognitive load associated with difficulties in reading in a different script. To speculate even further, the possible differences in the choice of scanpath reading processes might be affected by the typological language proximity in general: The more similar languages are (i.e., the same script, many cognates, syntactic similarity), the easier the transition to a fluent reading process is.

Another limitation of our investigation was the limited number of bilingual participants (60), which might have made it challenging to capture the effects of demographic factors. Thus, future studies with a higher number of HSs or L2 participants are needed; for now, the necessity to bring participants physically to the laboratory that houses the eye-tracking facilities remains a barrier to massive online collection of behavioral data that has recently become popular in psycholinguistics. Including a thorough examination of the impact that sociolinguistic and demographic factors have on the development of scanpath reading processes is, however, a promising direction for investigating the similarities and differences between children and bilingual readers.

Finally, we deliberately stayed away from exploring the relation between scanpath reading processes and comprehension accuracy within and between our groups of readers. Our choice of materials, namely, simple and unambiguous sentences appropriate for monolingual children, presupposed high accuracy in answering comprehension questions; indeed, accuracy was at ceiling for three of the four groups. Future studies should establish, however, how the ability to engage in a particular scanpath reading process affects the accuracy of comprehension of more complex sentences, or sentences with experimental manipulation, and whether the scanpaths in sentences that result in inaccurate comprehension are qualitatively different from the scanpaths in sentences accurately comprehended. If such a relation exists (e.g., a higher percentage of word skipping leads to lower accuracy in comprehension in bilingual readers), the results could contribute to the development of targeted literacy instruction in the nondominant language. We believe that exploring these questions in various populations and in different languages and scripts will provide fruitful lines of future investigation to advance the theories of psycholinguistics and bilingualism.

NOTES

The contribution to this work by Olga Parshina and Irina A. Sekerina was supported by a PSC-CUNY (Professional Staff Congress–City University of New York) Research Award (60616-00-48). The contribution of Anastasiya Lopukhina was funded by the Center for Language and Brain at HSE University via a Russian Federation Government grant (14.641.31.0004).

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Submitted May 28, 2020
Final revision received March 20, 2021
Accepted March 23, 2021

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APPENDIX A

Tables A1–A3 present the outcomes for the models and model equations referred to in the text.

TABLE A1
Comparison of the Eye Movement Characteristics Among the Three Scanpath Reading Processes

	Gaze duration (ms)			Skipping probability			Regression probability			Fixation count			Time to read a word (ms)			Total time to read a sentence (ms)		
Predictor	**Est.**	*SE*	*p*	**Est.**	*SE*	*p*	**Est.**	*SE*	*p*	**Est.**	*SE*	*p*	**Est.**	*SE*	*p*	**Est.**	*SE*	*p*
Reference: Fluent scanpath reading process																		
Intercept	6.1	0.05	**<.001**	.15	.01	**<.001**	.12	.01	**<.001**	1.9	0.13	**<.001**	0.95	0.04	**<.001**	8.0	0.05	**<.001**
Intermediate	0.20	0.02	**<.001**	−.05	.01	**<.001**	.14	.01	**<.001**	0.90	0.06	**<.001**	0.46	0.03	**<.001**	0.55	0.02	**<.001**
Beginner	0.33	0.02	**<.001**	−.08	.01	**<.001**	.27	.01	**<.001**	2.6	0.08	**<.001**	1.2	0.04	**<.001**	1.1	0.02	**<.001**
Reference: Beginner scanpath reading process																		
Intercept	6.5	0.05	**<.001**	.07	.01	**<.001**	.38	.01	**<.001**	4.4	0.13	**<.001**	2.2	0.04	**<.001**	9.1	0.05	**<.001**
Intermediate	−0.12	0.01	**<.001**	.03	.01	**<.001**	−.12	.01	**<.001**	−1.7	0.05	**<.001**	−0.75	0.03	**<.001**	−0.47	0.02	**<.001**
Fluent	−0.33	0.02	**<.001**	.08	.01	**<.001**	−.27	.01	**<.001**	−2.6	0.08	**<.001**	−1.2	0.04	**<.001**	−1.1	0.02	**<.001**
Random effects																		
σ^2		0.07			.01			.02			0.89			0.22			0.08	
$\tau_{00,\text{participants}}$		0.21			0.00			0.01			0.86			0.11			0.18	
$\tau_{00,\text{sentence}}$		0.02			0.00			0.00			0.19			0.02			0.02	
Observations		3,446			3,449			3,446			3,449			3,449			3,442	
R^2 / Ω^2_0		.046/.776			.053/.309			.204/.483			.308/.682			.349/.580			.323/.815	

Note. Est. = estimate; *SE* = standard error. Statistically significant differences are in boldface. Bonferroni correction applied.

TABLE A2
Summary Generalized Linear Mixed Models for the Scanpath Reading Processes for Heritage-Language Speakers

	Fluent				Intermediate				Beginner			
Predictor	**Est.**	*SE*	*p*	*d*	**Est.**	*SE*	*p*	*d*	**Est.**	*SE*	*p*	*d*
Fixed effects												
Intercept	−7.1	0.95	**<.001**		0.49	0.36	.516		−0.89	0.45	.150	
Age of arrival to the United States	0.41	0.31	.180	0.07	0.10	0.25	1	0.07	−0.40	0.34	.717	−0.12
Self-assessments												
Russian-language exposure	0.21	0.45	.1	0.22	−0.32	0.30	.876	−0.32	0.37	0.38	.972	0.22
Comprehension	0.63	0.51	.657	0.72	−0.30	0.34	1	−0.28	−0.26	0.43	1	−0.14
Reading pretests												
Russian Oral Reading Fluency test	2.6	0.57	**<.001**	1.6	0.21	0.30	1	0.14	−1.5	0.41	**<.001**	−1.2
English Oral Reading Fluency test	0.31	0.60	1	−0.32	0.24	0.29	1	0.26	−0.09	0.35	1	−0.09
Random effects												
$\tau_{00,sentence}$	1.8				0.125				0.497			
$\tau_{00,participant}$	1.6				2.1				3.1			

Note. Est. = estimate; *SE* = standard error. The cells with estimates in which there is a statistically significant effect are in boldface. Bonferroni correction applied.

TABLE A3
Summary Generalized Linear Mixed Models for the Scanpath Reading Processes for Second-Language Learners

	Fluent				Intermediate				Beginner			
Predictor	**Est.**	*SE*	*p*	*d*	**Est.**	*SE*	*p*	*d*	**Est.**	*SE*	*p*	*d*
Fixed effects												
Intercept	−3.7	0.70	**<.001**		0.90	0.50	.207		−1.5	0.58	**.033**	
Self-assessments												
Russian-language exposure	0.57	0.75	1	0.23	0.47	0.53	1	−0.31	−0.47	0.62	1	0.20
Comprehension	2.0	0.73	**.018**	0.71	0.23	0.44	1	−0.28	−0.72	0.51	.465	−0.13
Reading pretests												
Russian Oral Reading Fluency test	−0.64	0.89	1	1.7	0.66	0.59	.783	0.16	−0.65	0.69	1	−1.2
English Oral Reading Fluency test	0.36	0.46	1	−0.33	−0.34	0.33	.924	0.25	0.19	0.39	1	−0.07
Random effects												
$\tau_{00,sentence}$	0.291				0.495				0.725			
$\tau_{00,participant}$	2.0				2.1				2.8			

Note. Est. = estimate; *SE* = standard error. The cells with estimates in which there is a statistically significant effect are in boldface. Bonferroni correction applied.

APPENDIX B

The following is an example for the code used for fitting the generalized linear mixed model for testing the influence of the group membership on the scanpath reading process:

```
glmer(Fluent process ~monolingual + (1|sentence) + (1|id), data = strategies, family = binomial, control = glmerControl(optimizer = "bobyqa"))
```

The following is an example of the code used for fitting the generalized linear mixed model for testing the influence of the demographic and reading performance factors on the scanpath reading process by the HS group:

```
glmer(Fluent process ~Age_of_Arrival + Russian_daily_exposure + Comprehension + ORF_Rus + ORF_Eng + (1|sentence) + (1|id), data = HS, family = binomial, control = glmerControl(optimizer = "bobyqa"))
```