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Relating foveal and parafoveal processing efficiency with word-level parameters in text reading☆

Timo T. Heikkilä *, Nea Soralinna, Jukka Hyönä

University of Turku, Finland

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ABSTRACT

The study examined whether word-level eye-movement patterns in text reading can be predicted by individual differences in foveal and parafoveal word processing efficiency. Individual differences in lexical skills were gauged by presenting words and pseudowords with short exposure times in the fovea (30–60 ms) and at varying eccentricities in the parafovea. Lexical decision was used to index orthographic processing, word naming to index phonological processing and pseudoword naming to index grapheme-phoneme decoding. The Random Forests statistical technique was used to assess the relative importance of individual difference measures in predicting readers' eye-movement patterns. The results show that individual differences in foveal word processing efficiency are better predictors of both foveal and parafoveal word processing during reading than differences in parafoveal processing efficiency. Results indicate that individual variability in foveal word recognition skills are better determinants of reading fluency among adult readers than variability in parafoveal word recognition skills.

Introduction

Fluency in reading stems from the ability to recognize words, combine them into a sentence meaning and to combine the meanings of sentences to create a coherent understanding of larger segments of text. Fluency in each of these steps makes it possible to read efficiently and to comprehend the text. Efficient word recognition is a crucial part of this process, without which fluent reading is not possible.

Research has shown marked individual differences in reading fluency even among competent adult readers. In the current study, we examined to what extent word recognition and decoding abilities can predict variability in reading fluency among adult readers of Finnish. The key question was to examine the extent to which text reading efficiency can be explained by individual differences in word recognition skills under stringent time constraints and from variable visual eccentricities. To do this, we examined the role of foveal and parafoveal word processing skills as predictors of reading fluency. We measured processing efficiency in fovea and parafovea with three different word recognition tasks (lexical decision, word naming, and pseudoword naming) tapping into more implicit and explicit word recognition and gauging the use of the direct and indirect route to word identity (Coltheart et al., 2001) to assess their role in predicting reading fluency.

The function of fovea and parafovea in reading

During reading, only a relatively narrow area of the visual field can be utilized for visual information extraction. The useful field of view contains two parts known as the foveal and parafoveal areas. These areas have different roles in reading. The fovea is the part of the retina where visual acuity is at its best. The width of the fovea is approximately 2 degrees of visual angle, translating to about 6–8 letters from a normal reading distance. The parafovea is defined as the area that falls outside the boundaries of the fovea and extends approximately up to 5 degrees to both sides around the current fixation point. During reading, meaningful information (e.g., identities of words) is mostly extracted from the fovea. Parafovea, on the other hand, is used for preprocessing of the forthcoming text (for reviews, see e.g., Drieghe, 2011; Hyönä, 2011; Rayner, 1998). Parafoveal preprocessing facilitates the recognition of the word once it is foveally fixated - an effect known as parafoveal preview benefit (Rayner, 1975). Occasionally, a word may also be recognized parafoveally, in which case the word is skipped (i.e., not fixated).

There are individual differences in how effectively readers are able to extract information from the foveal and parafoveal areas (Rayner, 1975). Studies have focused on examining the extent to which efficiency

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* Corresponding author at: Department of Psychology and Speech-Language Pathology, University of Turku, FI-20014 Turku, Finland.
E-mail address: timo.t.heikkila@utu.fi (T.T. Heikkilä).

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in foveal and parafoveal processing can be explained by individual variability in reading skill among adult readers. We summarize the existing literature in Tables 1 and 2. Table 1 reviews the studies on individual differences in foveal processing, while Table 2 does that for parafoveal processing. We conducted a literature search in Web of Science (November 2023) and chose in the summary all the studies that fulfilled the following criteria: (1) The study used eye-tracking to examine individual differences in foveal or parafoveal processing during reading of sentences or texts; (2) individual differences were measured with tests gauging reading-related cognitive abilities; (3) the study reported word-level measures of reading; (4) the sample consisted of adult readers (excluding special populations); (5) reading was done in participants' native language.

As is evident from the reviewed literature, individual differences in the efficiency in using foveal and parafoveal information is associated with variability in reading ability. The vast majority of these studies has been conducted with English-speaking samples and materials. Reading skills have been assessed with a plethora of different tests. The used tests measure different aspects of reading ability including reading comprehension ability, reading fluency, rapid automatized naming ability, spelling ability, vocabulary knowledge, amount of print exposure and word identification skills.

Reading comprehension tests not only measure online comprehension ability but also text memory (remembering facts of the text after reading). Variability in readers' exposure to print is tested by the Author Recognition Test (ART; Stanovich & West, 1989) that assesses how many names of fiction authors readers recognize from a list of names by relying on long-term memory. At present, ART may not adequately capture the magnitude of print exposure particularly among younger people, as people's reading habits are changing. They devote increasingly more time to reading online materials (blogs, news, social media, etc.) instead of more traditional printed materials (fiction and nonfiction books). In the rapid automatized naming (RAN) task, individuals are to name aloud as quickly as possible a set of familiar items on a page that can be letters, numbers, colors or objects. RAN taps into individual ability in fast retrieving from long-term memory phonological representations of different objects. Thus, its relation to basic processes in foveal and parafoveal text processing is quite indirect. Tests of vocabulary knowledge assess the size of the readers' vocabulary. Finally, spelling ability (writing from dictation and recognizing spelling mistakes) reflects the lexical quality of readers' orthographic word representations.

Individual differences in foveal processing

In the literature search, we identified 20 studies that have investigated the link between reading skills and foveal word processing. The studies are summarized in Table 1. Individual differences in ART and RAN are among measures that successfully predict fixation times on words during reading. The nature of these associations is such that greater measured print exposure leads to more efficient reading, exhibited as shorter fixation times on words. According to Kuperman et al. (2016), among adult readers the predictive power of RAN is strongly related to the individual skill and fluency in sequential eye-movement control during reading. Analogously, Gordon et al. (2019) conclude that RAN "reflects efficient coordination of perceptual-motor and attentional processing during reading" (p. 553). Individual differences in vocabulary size and literacy skills (a combination of word recognition skills and reading fluency) also predict fixation times on words. Finally, spelling ability is associated with the size of the word frequency effect.

Individual differences in parafoveal processing

Our literature search identified 13 studies investigating individual differences in parafoveal word processing during reading. These studies are summarized in Table 2. Yet, it should be noted that some of the studies summarized in Table 1 not only examined foveal processing but also parafoveal processing as indexed by the probability of word skipping (when a word is skipped, it is assumed to be identified in the parafovea). Three studies on the use of parafoveal information have utilized the gaze-contingent moving window paradigm (McConkie & Rayner, 1975). In this paradigm, text is made visible only within a text window that moves along with the reader's gaze, while all other text outside the window is visually masked. By manipulating the number of letters visible in the window, it is possible to determine the size of the perceptual span from which the reader extracts useful visual information. The size of the perceptual span is estimated by the window size resulting in a similar reading speed as the baseline condition where the text is read normally without a window.

Reading skill measurements in moving window studies include measures of print exposure, decoding ability, RAN, vocabulary size, reading comprehension, word identification and spelling ability. As is apparent from Table 2, the results indicate that more skilled readers are able to benefit from larger window sizes and read faster especially when no window was present. Moreover, they make longer saccades and less fixations than less skilled readers. These results suggest that skilled readers have a wider perceptual span than less skilled readers.

Another experimental method used is the boundary paradigm (Rayner, 1975), also known as the gaze-contingent display change paradigm. Seven studies summarized in Table 2 adopted this paradigm, where the form of target words presented in the parafovea is manipulated (i.e., a parafoveal preview is presented that is orthographically, phonologically or semantically related to the target word). During the incoming saccade to the target that crosses a preset invisible boundary the preview is changed to its correct form. Due to saccadic suppression, readers are most of the time unable to detect the change taking place during the saccade. The paradigm yields an estimate of the type and amount information processed in the parafovea.

Similar to the moving window studies, the boundary studies adopted a number of different reading ability measures including reading comprehension, spelling, vocabulary knowledge, working memory capacity and letter identification. Better readers consistently skip over words more frequently than poorer readers. This is also evident from the three studies using a sentence reading paradigm (see Table 2) and from several studies summarized in Table 1. Moreover, boundary studies report evidence suggesting that individual differences and type of parafoveal previews interact. More skilled readers exhibited increased skipping of words with high-frequency previews than nonword previews (Veldre & Andrews, 2015a); skilled readers gained increased preview benefit from homophone than orthographic previews (Chace et al., 2005); readers with good spelling ability showed reduced benefit from semantically related previews (Veldre & Andrews, 2016a); less proficient readers showed a plausibility preview effect (semantically plausible previews resulted in shorter word reading times than implausible previews), whereas proficient readers did not show the effect (Veldre & Andrews, 2016b).

To sum up, our literature review demonstrates that individual differences in different components of reading ability among adult readers can predict foveal and parafoveal processing during sentence and passage reading. A subset of the reported results may be explained by the Lexical Quality Hypothesis (LQH; Perfetti, 2007). Lexical quality refers to the precision, specificity and stability of words' form (orthography and phonology) and meaning representations. Good lexical quality representations are precise, fully specified and stable. Form and meaning representations are also well bound together, and meaning representations are context-independent. LQH states that lexical quality contributes to reading comprehension. Readers possessing good-quality lexical representations can retrieve word identities and meaning with little effort, resulting in improved efficiency of reading. A consequence of effortless word recognition is fast word processing. In sum, LQH posits that lexical quality "determines the accuracy and fluency of word

Table 1
Summary of studies on individual differences in foveal processing ordered by the date of publication.

Study	Participants	Individual difference measures	Key results
Everatt & Underwood, 1994	English speaking university students and staff (n = 36; n of items = 36)	Mill-Hill synonym selection test (vocabulary size), GAPADOL (reading comprehension), lexical decision task (reaction times)	Reading comprehension score correlated negatively with gaze durations on target words. Correlations between gaze duration and vocabulary size and reaction times in lexical decision were non-significant.
Jared et al., 1999	English speaking university students (Exp. 4: n = 48, n of items = 54; Exp. 5: n = 48, n of items = 108; Exp. 6: n = 48, n of items = 108)	Nelson-Denny Reading Test[1] (Comprehension subtest)	Good comprehenders had shorter fixation times on target words than poor comprehenders. Both reader groups produced a word frequency effect of similar size. Good comprehenders had significantly longer gaze durations on homophone errors than on correct target words, but similar gaze durations on homophone errors and spelling control errors (Exp. 4–5). This pattern is taken to suggest that good readers use the direct visual route to word identity. Poor comprehenders had similar gaze durations on homophone errors and correct control words, whereas homophone errors produced shorter gaze durations than spelling control words (Exp. 4–6). The pattern suggests that the phonological route plays an important role in word recognition among poor comprehenders.
Ashby et al., 2005	English speaking university students (n = 44; n of items = 32)	Nelson-Denny Reading Test	Highly skilled readers had shorter reading times than average skilled readers. In a non-constraining sentence context, processing of low-frequency words was harder for the average than high-skilled readers. Average readers also made more regressions than highly skilled ones. In a highly constraining sentence context, reading of highly skilled readers was relatively unchanged compared to the non-constraining sentences. On the other hand, average readers were slower to recognize unpredictable, low-frequency words and had to rely on context to support the recognition of predictable low-frequency words.
Kuperman & Van Dyke, 2011	English speaking, non-college-bound young adults (n = 71; n of items = 81)	CTOPP (phonological awareness with words and nonwords, phonological awareness with memory load, rapid naming), WID (decoding), WATT (decoding), Nelson-Denny Comprehension Test, SDRT (fast reading subtest), PIAT-R (reading comprehension, listening comprehension), Sentence span task (verbal working memory)	RAN and word identification (test of decoding skill) were found to be the best predictors of eye-movement behavior for the whole time-course of reading. These predictors also exhibited effects larger in magnitude than the effects of word length and frequency and strongly modulated the effects of word length and frequency on fixation durations.
Kuperman & Van Dyke, 2013	English speaking, non-college-bound young adults (n = 71; n of items = 81)	WID (word identification) taken as a proxy of vocabulary size	Skilled readers read words with shorter gaze durations than less skilled readers. Less skilled readers displayed a greater word frequency effect than skilled readers when corpus frequencies were used, but not when subjective frequencies were used.
Frisson et al., 2014	English speaking university students (n = 54; n of items = 128)	Gray Silent Reading Test (GSRT) of comprehension ability	Good and poor comprehenders had largely similar eye movement patterns. Word primes containing both orthographic and phonological overlap with the targets produced an inhibition effect for the target word reading among good comprehenders, when the prime and the target were separated by several words (an average of 8.8. words) within a sentence, but a tendency for facilitation for poor comprehenders. This pattern was taken to suggest that good comprehenders keep lexical representations active across larger chunks of text than poor comprehenders.
Falkauskas & Kuperman, 2015	English speaking university students (n = 29; n of items = 120)	ART[1], MRT	Readers with higher scores on ART displayed shorter fixation durations than those with lower scores on ART. Readers with high scores on ART showed a spelling bias (compound words presented in their preferred format, spaced versus unspaced, benefit from a processing advantage) in total fixation time, but readers with low scores did not. Second fixation duration displayed a three-way interaction between spelling bias, word frequency and ART. All readers showed a spelling bias for high-frequency compound words, but the effect did not occur for low-frequency compound words for readers with low scores on ART.
Kuperman et al., 2016	English speaking university students (Study 1: n = 53, n of items = 5; Study 2: n = 85, n of items = 4)	Incrementally more complex variations of RAN[1] with differing task demands related to articulation, activation of phonological codes, retrieval of lexical information, oculomotor coordination and attentional cues	Good RAN ability was associated with overall efficiency of eye-behavior during reading. RAN was found to index the fluency and skill level of sequential eye-movement control during reading.
Taylor & Perfetti, 2016	English speaking adults (n = 35, n of items = 68 paragraphs with a mean of 95 words each)	Five dimensions determined by factor analysis: reading experience, lexical knowledge, accuracy focus, learning and memory, and casual reading.	Participants with more reading experience showed more skipping, fewer number of refixations, less re-reading and shorter refixations. Participants with good

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Table 1 (*continued*)

Study	Participants	Individual difference measures	Key results
			lexical knowledge showed more skipping, shorter first-fixation durations on high-frequency words and fewer refixations.
Veldre et al., 2017	English speaking university students (n = 109; n of items = 120)	Nelson-Denny Reading Test^2 (reading comprehension, vocabulary), spelling dictation test (SDT), spelling recognition test (SRT)	Reading a normal text with interword spaces preserved, individuals with good reading comprehension ability read the target words with shorter gaze durations than those with poorer comprehension ability. Good spellers skipped over more words and made longer saccades than poorer spellers; good spellers also showed a smaller word frequency effect than poorer spellers. Good spellers were less affected than poorer spellers by the removal of interword spaces or by their replacement with numbers or capital letters. However, reading comprehension ability did not modify the spacing effects.
Lowder & Gordon, 2017	English speaking university students (n = 48; n of items = 32)	ART^2	Better performance in ART resulted in shorter reading times. Better performance in ART led to no repetition priming effect (the same word repeated across two consecutive sentences), whereas a lower performance led to a robust repetition effect implicating that lower print exposure is associated with poorer-quality linguistic representations.
Kuperman et al., 2018	English speaking university students (n = 51; n of observations = 12762)	Comparative reading habits survey, ART^1 and magazine recognition test (MRT), Test of Word Reading Efficiency (TOWRE), Vocabulary Size Test, WASI^1 (Verbal IQ, Reasoning IQ), RAN^2, eye-movement records on the RAN^2 grid, Finger Tapping	Good performance in linguistic and cognitive measures was related in the sentence level to greater word skipping, shorter reading times, less fixations and better reading comprehension. Reading fluency measures, RAN and self-reported proficiency and interest in reading were highly reflected in eye-movement measures. Vocabulary size, performance in ART and RAN were highly related to reading comprehension. In the word level, vocabulary size, reading fluency, RAN and self-reported proficiency and interest in reading were associated with greater word skipping, shorter first fixation durations and shorter gaze durations.
Schmidtke et al., 2018	English speaking young adults (n = 138; n of observations = 5724)	Composite score of ART^1 and MRT (print exposure), composite score of PPVT and WASI^1 (vocabulary size), TOWRE (word recognition skill)	Readers with greater exposure to print and larger vocabulary were helped more by semantic transparency in reading compound words than those with less print exposure or smaller vocabulary, as revealed by total fixation time on compound words. Readers with greater print exposure or larger vocabulary also demonstrated generally shorter total fixation times than those with less print exposure or smaller vocabulary.
Gordon et al., 2019	English speaking university students (n = 546; n of items = 30–60)	ART^2, RAN^3	Better performance in ART was related to higher skipping rate and shorter gaze durations. Higher ART scores were also associated with less processing difficulty due to long and low-frequency words. Better performance in RAN led to shorter gaze durations, shorter second-pass reading times and smaller amount of first-pass regressions. Better RAN scores were also associated with a reduced word-frequency effect in reading time and with a greater word-frequency effect of the previously fixated word.
Payne et al., 2020	English speaking, age range16–64 years (n = 80; n of observations = 87106)	SORT (word recognition), WRF (reading fluency), WASI^2 (fluid intelligence, crystallized intelligence), Letter and pattern comparison tasks (psychomotor speed)	Literacy level was estimated by the two language tasks. First-pass reading times and total reading times were longer and reading rate slower for readers with low literacy. First-pass fixation times were not slower for all words for low-literacy readers but instead low-literacy level exhibited more increased intra-individual variability in first-pass fixation durations. Reading patterns of lower literate adults showed more variability expressed e.g. in extremely long first-pass fixation durations on some words. Lower literacy level also resulted in more regressions, more first-pass refixations and less word skipping.
Korinth et al., 2020	German speaking university students (n = 24; n of observations = 51216)	Measurements of foveal and parafoveal crowding sensitivity (FCS, PCS)	Wider spacing between letters slowed down reading of fast readers but not for slow readers. However, no association of parafoveal or foveal crowding sensitivity was observed with how wider letter spacing influenced any of the measured eye-movement parameters.
Andrews & Veldre, 2021	English speaking university students (n = 95; n of observations = 20937)	Composite score of Nelson-Denny Reading Test^2 and spelling ability (SA; dictation, recognition)	Proficient readers had shorter fixation times on target words than less proficient readers. Less proficient readers displayed a larger sentence wrap-up effect in go-past fixation time than proficient readers. Proficient

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Table 1 (*continued*)

Study	Participants	Individual difference measures	Key results
			readers are assumed to delay integrative wrap-up processing, whereas less proficient readers engage in immediate wrap-up processing to compensate for their reduced efficiency in incremental online integration.
Cheimariou et al., 2021	English speaking university students (n = 26) and community members (n = 27; 60–76 years of age; n of items = 20)	Composite score of vocabulary subtest of WAIS-IV, ART[1] and NAART (reading aloud words with irregular spellings)	Readers with high verbal ability showed a word predictability effect in first fixation duration, whereas readers with low verbal ability did not. This suggests that good verbal ability increases the automaticity of initial word processing.
Moss et al., 2023	English speaking university students (n = 90; no of items = 6)	Working memory capacity (WMC) estimated by operation span	Individuals with high WMC displayed longer total fixation times on words (and more regressions) than those with low WMC. Such an effect was not observed for gaze duration. Readers with high WMC spent more total fixation time on text segments central than peripheral to the overall meaning of the passage. This was found in the condition where the comprehension questions were presented after reading the passage. Such effect was not obtained for low WMC readers.
Gong & Shuai, 2023	English speaking community members (n = 44; n of observations = 15733)	PPVT (vocabulary), WASI[1] (vocabulary), PIAT-R (listening comprehension), WID (decoding), WATT (decoding), PIAT-R (reading comprehension), GORT-COMP (reading comprehension), GORT-WPM (oral reading fluency), Sentence Span Task (working memory)	Readers with poor listening comprehension and vocabulary displayed in gaze duration a greater word length effect than their more proficient peers. Similarly, low working memory capacity readers showed in gaze duration a greater word length effect than high working memory capacity readers. Readers with low levels of oral reading fluency had longer total fixation times on words than readers with high levels of oral reading fluency. Readers with high oral fluency produced a bigger sentence wrap-up effect than those with low oral fluency. The same was true for readers with low working memory capacity. High decoders make more regressions from the sentence-final words than poor decoders.

ART[1] = Author Recognition Test (Acheson et al., 2008); ART[2] = Author Recognition Test (Moore & Gordon, 2015); Comparative reading habits survey (Acheson et al., 2008); CTOPP = Comprehensive Test of Phonological Processing (Wagner et al., 1999); Finger Tapping (Carello et al., 2002); FCS = Foveal crowding sensitivity (Haase & Hohmann, 1982); GAPADOL (McLeod & Anderson, 1973); GORT-COMP = Gray Oral Reading Test (Wiederholt and Bryant, 2001); GORT-WPM = Gray Oral Reading Test, Words Per Minute (Wiederholt and Bryant, 2001); Gray Silent Reading Test (Wiederholt & Blalock, 2000); Letter and pattern comparison tasks (Salthouse, 1996); Mill-Hill synonym selection test (Raven et al., 1977); MRT = Magazine recognition test (Acheson et al., 2008); NAART = North American Adult Reading Test (Blair & Spreen, 1989); Nelson-Denny Comprehension Test (test version not specified); Nelson-Denny Reading Test (test version not specified); Nelson-Denny Reading Test[1] (Brown et al., 1981); Nelson-Denny Reading Test[2] (Brown, et al., 1993); PCS = Parafoveal crowding sensitivity (modifed version of task in Tadin et al., 2012); PIAT-R = Peabody Individual Achievement Test-Revised (Markwardt, 1998); PPVT = Peabody Picture Vocabulary Test 4th Edition (Dunn & Dunn, 1981); RAN[1] = Rapid Automatized Naming; RAN[2] = Rapid Automatized Naming (Denckla & Rudel, 1974); RAN[3] = Rapid Automatized Naming (Comprehensive Test of Phonological Processing, Wagner et al., 1999); SA = Spelling ability (Andrews et al., 2020); SDRT = Stanford Diagnostic Reading Test (Karlson & Gardner, 1995); Sentence span task (Listening version of the test, Daneman & Carpenter, 1980); SORT = The Slosson Oral Reading Test (Slosson & Nicholson, 1990); SDT = Spelling dictation test (Andrews & Hersch, 2010); SRT = Spelling recognition test (Andrews & Hersch, 2010); TOWRE = Test of Word Reading Efficiency (Torgesen et al., 1999); Vocabulary size test (Nation & Beglar, 2007); WAIS-IV = The Wechsler Adult Intelligence Scale—Fourth Edition (Wechsler, 2008); WASI[1] = Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999); WASI[2] = The Wechsler Abbreviated Scale of Intelligence (Wechsler, 1981); WATT = Woodcock-Johnson-III Test of Achievement Word Attack subtest (Woodcock et al., 2001); WID = Woodcock-Johnson-III Word Identification subtest (Woodcock et al., 2001); WMC = Working memory capacity (Automated operation span task, Unsworth et al., 2005); WRF = Woodcock–Johnson Reading Fluency task (Schrank et al., 2014).

identification" (p. 377, Perfetti, 2007) and that there is a link between lexical quality and comprehension.

Measures of print exposure (ART), spelling ability, vocabulary knowledge and decoding skills are likely to reflect different aspects of readers' lexical representations. Spelling ability reflects the quality of readers' orthographic representations of words, while measures of decoding skill presumably tap into the quality of phonological representations. However, it is less clear what lexical representations are gauged by measures of print exposure. What is common to many previous studies is that the quality of lexical representations was measured with tests that contained no time pressure. That is, participants had ample time to choose the correct spelling in the spelling recognition test or authors from a list of authors and non-authors. Non-timed tests are likely to gauge the precision of lexical representations. Another key feature of lexical representations contributing to efficient reading is that they are activated fast in readers' minds. The present study focuses on this aspect of lexical processing.

Some studies demonstrate that the same individual difference measures predict both foveal and parafoveal processing, as indexed by word fixation times and word skipping probability, respectively (Gordon et al., 2019; Kuperman et al., 2018; Payne et al., 2020). On the other hand, moving window studies show that good readers have a larger perceptual span than poorer readers (see Table 2). Yet, it is not known to what extent foveal and parafoveal processing skills reflect a common underlying ability. One possibility is that high-quality lexical representations are readily available for both foveal and parafoveal processing. In other words, high-quality representations may be readily activated also with less precise stimuli available in the parafovea. Yet, it is also possible that individual differences in perceptual span constitute at least a partly independent skill. The present study was designed to shed light on this issue.

Quality of lexical representations measured with lexical decision and naming combined with short exposure durations

In the present study, we gauged individual differences in the quality of lexical representations by presenting words and pseudowords with short exposure times in the fovea and parafovea. The key idea was that efficient word recognition is characterized by fast word processing. Two recognition tasks were employed, lexical decision and naming. To

Table 2
Summary of studies on individual differences in parafoveal processing ordered by the date of publication.

Study	Study method	Participants	Individual difference measures	Key results
Kennison & Clifton, 1995	boundary	English speaking university students (n = 48; n of items = 64)	Reading Span Test (working memory capacity)	Low-span readers had longer gaze durations on the boundary and target words than high-span readers. Low-span readers also skipped less often boundary and target words than high-span readers. High-span readers made better use of parafoveal previews in skipping. However, the parafoveal preview benefit in fixation time did not differ between the groups.
Chace et al., 2005	boundary	English speaking adults (n = 32; n of items = 64)	Nelson-Denny Reading Test (reading comprehension, vocabulary)	Skilled readers were able to obtain more preview benefit from homophone previews than from orthographic previews. This was not shown for less skilled readers. This indicates that less skilled readers do not use phonological codes for integration across eye movements or show normal preview benefit effects.
Risse, 2014	boundary	German speaking high-school and university students (n = 57; n of items = 120)	Flanker-letter identification (FLI) in parafovea (visual span) and fovea	Individual differences in identifying single letters (visual span) did not correlate with the size of the parafoveal preview benefit (difference between valid and invalid preview) or with gaze durations on target words. However, the visual span score correlated positively with global reading rate.
Veldre & Andrews, 2014	moving window	English speaking university students (n = 45; n of items = 64)	Nelson-Denny Reading Test[2] (vocabulary, reading comprehension), spelling ability (dictation, recognition)	Performance of skilled readers was best when all letters were visible in the text window. Performance of the less skilled did not improve beyond the windows size of 11 letters. Saccades of more skilled readers were longer than those of less skilled readers, when no window was present.
Veldre & Andrews, 2015a	boundary	English speaking university students (n = 94; n of items = 52)	Nelson-Denny Reading Test[2] (reading comprehension), spelling ability (dictation, recognition; SDT, SRT)	Skilled comprehenders were able to extract more information from the parafovea than less skilled comprehenders. This was evident as more skipping of words with high-frequency previews than nonword previews. When high-frequency preview words were not skipped, skilled readers received no preview benefit in single fixations. For those with superior spelling ability the parafoveal manipulation caused lateral inhibition for words similar to the target word. Less skilled readers showed increased rereading after high-frequency previews that suggests integration difficulties.
Veldre & Andrews, 2015b	boundary	English speaking university students (n = 107; n of items = 40)	Nelson-Denny Reading Test[2] (reading comprehension), spelling ability (dictation, recognition)	High reading and spelling ability was associated with larger preview benefit across first-pass reading measures. Evidence suggested that orthographic precision of reader's lexical representations explain the parafoveal processing advantage and that this advantage is partly due to efficient foveal processing.
Choi et al., 2015	moving window	English speaking university students (n = 70; n of items = 80)	ART[3], comparative reading habits, circle targeting task (oculomotor processing speed), WRMT-III subtests: word identification (decoding words); word attack (decoding nonwords); listening comprehension; rapid automatized naming	Readers with better language abilities had larger perceptual spans. Readers with good language abilities were able to benefit from the no-window condition relative to 16-character window. Readers with poorer abilities showed no improvement after 12-character windows. Language ability was a more reliable predictor of perceptual span than oculomotor processing speed. Skilled readers had faster reading rates and larger saccade amplitudes even in the smallest window condition.
Eskenazi & Folk, 2015	sentence reading	English speaking university students (n = 62; n of items = 54)	Nelson-Denny Reading Test (vocabulary, reading comprehension)	Low-skilled readers read target words slower when preceded by high-load words. This was not true for high-skilled readers. Low-skilled readers skipped 3-letter words less often than high-skilled readers when the foveal load from the previous word was high. Words with low foveal load did not produce differences in skipping 3-letter words between skilled and less skilled readers. Reading skill did not have an effect in skipping 5-letter words.
Veldre & Andrews, 2016a	boundary	English speaking university students (n = 99; n of items = 72)	Nelson-Denny Reading Test[2] (vocabulary, reading comprehension), spelling ability (dictation, recognition)	Individuals with good comprehension and spelling abilities read the target words with shorter gaze durations and were more likely to skip words than those with poorer comprehension and spelling abilities. Readers with good comprehension abilities benefited equally from identical and semantically related parafoveal previews. In contrast, good spellers showed reduced benefit from semantically related previews, which were no better than semantically unrelated previews.

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Table 2 (*continued*)

Study	Study method	Participants	Individual difference measures	Key results
Veldre & Andrews, 2016b	boundary	English speaking university students (n = 97; n of items = 80)	Nelson-Denny Reading Test[2] (vocabulary, reading comprehension), spelling ability (dictation, recognition)	A composite score (first principal component) of reading comprehension and spelling ability was used as an index of relative reading proficiency. Proficient readers read the target words with shorter gaze durations and skipped them more often than less proficient readers. Less proficient readers showed a plausibility preview effect (semantically plausible previews resulted in shorter word reading times than implausible previews). However, proficient readers did not show this effect.
Slattery & Yates, 2018	sentence reading	English speaking university students (n = 92; n of items = 54)	Spelling ability (dictation, recognition; SDT, SRT), measure of effective reading rate (words per minute multiplied by the proportion of correctly answered comprehension questions)	Individuals with good spelling ability skipped over words more frequently and made longer saccades than those with poorer spelling ability. On the other hand, reading ability modulated gaze durations on target words: good readers displayed shorter gaze durations than poorer readers. Word-length effects were not modified by spelling ability.
Drieghe et al., 2019	sentence reading	English speaking university students (n = 95; n of items = 60)	Nelson-Denny Reading Test[2] (vocabulary, reading comprehension), spelling ability (dictation, recognition; SDT, SRT)	Better spellers skipped over more words than poorer spellers. An analogous effect was obtained for reading ability. Individuals with good reading comprehension ability read the target words with shorter gaze durations than those with a poorer comprehension ability.
Veldre et al., 2021	moving window	English speaking, ages 60–88 (n = 49; n of items = 126)	Nelson-Denny Reading Test[2] (vocabulary, reading comprehension, reading rate), dictation and recognition tests of spelling ability (SA), ART[2]	Better readers were able to utilize parafoveal information from the right side up to 15 characters, less skilled readers up to 9 characters. No differences related to reading ability were observed in the left parafoveal field. Those with better reading skills read faster by making less fixations and regressions than those with poorer reading skills.

ART[2] = Author Recognition Test (Moore & Gordon, 2015); ART3 = Author Recognition Test (Stanovich & West, 1989); Comparative reading habits (Acheson et al., 2008); FLI = Flanked-letter identification task (Legge et al., 2001); Nelson-Denny Reading Test (test version not specified); Nelson-Denny Reading Test[2] (Brown, Fishco, & Hanna, 1993); Reading Span Test (Daneman & Carpenter, 1980); WRMT-III = Woodcock Reading Mastery Tests-III (Woodcock, 2011); SA = Dictation and recognition tests of spelling ability (Andrews et al., 2020); SDT = Spelling dictation test (Andrews & Hersch, 2010); SRT = Spelling recognition test (Andrews & Hersch, 2010).

measure foveal processing efficiency, we varied the duration of stimulus presentation (30–60 ms). As shorter stimulus durations will make word recognition more difficult, good performance especially with the shorter stimulus durations is taken as an index of efficient foveal processing. Parafoveal processing efficiency was gauged by presenting the stimuli briefly (150 ms) at varying eccentricities in the parafovea. As pushing the stimulus further into the parafovea will make its recognition increasingly difficult, good performance particularly with the farthest distance is taken as an index of efficient parafoveal word processing.

The idea behind using two recognition tasks, lexical decision and naming, is that they likely reflect different aspects of the recognition process. Lexical decision is assumed to measure earlier levels of word identification, where the classification between a word and a pseudoword may be made without explicit stimulus recognition. According to one theory (Grainger & Jacobs, 1996), lexical decisions can be made on the basis of orthographic representations. A *yes* response is given, if the global activation for a word stimulus reaches a threshold within a certain timeframe, otherwise a *no* response is given. On the other hand, to name aloud a word or a pseudoword, its phonological representation needs to be activated. According to the dual route cascaded model (Coltheart et al., 2001), letter features activate the word's representation in the orthographic lexicon, which in turn activates the corresponding representation in the phonological lexicon. With the help of the phonological representation, the word may then be named aloud. However, this direct route from orthography to phonology cannot be used for naming aloud pseudowords, for which the reader does not have entries in the phonological lexicon. Instead, according to the theory, pseudowords are named by applying the grapheme-phoneme correspondence rules by decoding letters into phonemes. This route to word pronunciation is often called the indirect route. In order to measure the operation of these two routes, we included in our predictors both the word naming and the pseudoword naming task. Successful performance in both tasks require access to the word's phonological representation, which is assumed to take place after access to the word's orthographic representation measured by the lexical decision task.

Above, we argue that lexical decision and naming may reflect different stages of word processing. The E-Z Reader model (Reichle et al.,1998, 2009) designed to simulate eye movements in reading also postulates two stages of word recognition, coined the L1 and L2 stage. In the earlier L1 phase, a word is processed to a level where eventual lexical access is imminent and will be completed soon. When this level of processing is achieved, programming a saccade towards the next word in the text is commenced. Lexical access is then completed during the later L2 stage leading to explicit word identification. We speculate that the L1 phase may be associated with the performance in lexical decision, where a decision can be made when stimulus processing has reached a level where the letter cluster feels familiar enough to be classified as a word (otherwise a *no* response). Responses made on the basis of incomplete word recognition are especially likely with short stimulus exposure times, as was the case in the present study. Successful naming of a word, on the other hand, requires access to the word's phonological code activated via orthographic processing. Although words can be named without semantic access, the word meaning is also activated given it is available in the reader's vocabulary. Thus, it may be argued that word naming reflects the L2 stage. Finally, pseudoword naming differs from word naming in that it is entirely based on grapheme-phoneme decoding.

Current study

The present study departs from the existing studies in several important respects. First, we examined individual foveal and parafoveal word processing skills by presenting the foveal stimuli using short exposure times (e.g., Rayner et al., 2003) and the parafoveal stimuli in different eccentricities (e.g., Hyönä & Koivisto, 2006; Rayner & Morrison, 1981; Veldre et al., 2023a, 2023b). As argued above, our tasks are assumed to measure the activation of lexical representations, particularly orthographic and phonological representations, in the readers' mental lexicon (see also below). Second, we investigated individual differences in foveal and parafoveal processing efficiency among the same readers, which allowed us to assess their relative contribution to predicting readers' eye movement patterns during continuous text reading. Third, we used three different word recognition tasks (see above) to tap into varying aspects and stages of word processing. The lexical decision task is assumed to index global activation during early stages of word processing, presumably mostly at the orthographic level, that does not necessarily lead to full lexical access. Word naming, on the other hand, is assumed to index the activation of orthographic and phonological representations most likely also leading to the activation of the word's meaning. Finally, pseudoword naming is taken to reflect the indirect grapheme-phoneme conversion route.

Fourth, the study was conducted in Finnish; almost all previous studies have been conducted in English (see Table 1 and 2). Finnish is quite unique among the alphabetic scripts, as it has a practically perfect one-to-one mapping between graphemes and phonemes. Thus, just knowing how each phoneme is pronounced, anybody can read aloud Finnish without knowing a single word in the language. Another feature of Finnish is its rich morphology. In principle, every noun can appear in 2000 different inflectional forms. Even in practice, tens of different forms are used for each noun (in a newspaper corpus, an average of 52 forms were found for the most common Finnish nouns, see Nikolaev et al., 2022). Due to these features, the indirect grapheme-phoneme route is utilized in word recognition to a great extent by developing readers of Finnish (Schroeder et al., 2022). It is possible that it continues to be used by adult readers.

The main aim of the present study was to examine the extent to which word-level eye movement patterns in normal text reading can be predicted by individual differences in foveal and parafoveal processing efficiency among adult readers. Foveal processing during text reading was measured by the duration of the initial fixation made on a word, gaze duration (summed duration of fixations during the first-pass reading), and the probability of refixating a word. Parafoveal processing during reading was gauged by the probability of word skipping and the length of between-word saccades.

We used the Random Forests statistical technique (see Kuperman et al., 2018; Matsuki et al., 2016) to simultaneously assess the relative importance of our individual difference measures in predicting readers' eye movement patterns. This non-parametric regression technique is well suited in situations with a large number of collinear predictors. The problem of model overfitting can also be avoided using this technique. It is an exploratory method to identify the best predictors among a set of multiple collinear predictors. After identifying the best individual difference predictors for each dependent measure, we computed linear mixed effects models by adding word frequency and word length as the fixed effects, in addition to the individual difference measure. This way we were able to assess how word frequency and word length may modulate the influence of the individual difference measure.

Hypotheses

Next, we outline possible hypotheses regarding the relationship between individual differences in foveal and parafoveal word processing efficiency and foveal and parafoveal processing during text reading. We sketch hypotheses separately for foveal and parafoveal processing in reading.

Foveal processing in reading

An obvious prediction is that individual differences in foveal word recognition efficiency should be related to foveal processing in reading, as indexed by first fixation duration, gaze duration and probability of refixation. Moreover, foveal word processing efficiency estimated by shorter stimulus exposure times should be better predictors than those estimated by longer stimulus presentation times. If lexical decision indeed reflects early stages of word processing, the task should be a particularly good predictor of first fixation duration in reading. As the Finnish script possesses a perfect grapheme-phoneme correspondence, it is possible that the indirect grapheme-phoneme conversion route is also utilized in reading among adult participants, not only by children. If this is indeed the case, the pseudoword naming task should be a good predictor of foveal processing. On the other hand, if word naming and/or lexical decision outperforms pseudoword naming, it suggests that grapheme-phoneme decoding plays a less significant role among adult readers.

Regarding possible modulation of individual differences by word frequency and/or word length, it may be predicted that individual differences in foveal word processing efficiency are especially noticeable in reading infrequent (Ashby et al., 2005; Gordon et al., 2019; Kuperman & Van Dyke, 2011, 2013; Veldre et al., 2017; but see Jared et al., 1999) and long words (Gong & Shuai, 2023; Gordon et al., 2019; Kuperman & Van Dyke, 2011; but see Slattery & Yates, 2018). This is because even less skilled readers are likely to have less problems in recognizing frequent and short words during reading.

Parafoveal processing in reading

As is evident from the previous literature presented in Table 2, the size of the perceptual span has been linked to the probability of word skipping and saccade length. Thus, an obvious prediction is that individual differences in parafoveal word processing efficiency should predict parafoveal processing in reading, as indexed by probability of word skipping and between-word saccade length. Moreover, parafoveal processing efficiency estimated by performance with greater stimulus eccentricities should be a better predictor than that estimated using smaller eccentricities. If word skipping in reading is a result of more elaborate lexical processing, word naming or pseudoword naming should be a better predictor than lexical decision. As word skipping in reading is primarily confined to short and frequent words, observed individual differences may be limited to those words (Eskenazi & Folk, 2015; Veldre & Andrews, 2015a).

It is also possible that foveal processing efficiency would predict parafoveal processing in reading. Such a prediction may be derived from the E-Z Reader model (Reichle et al.,1998, 2009). The model assumes that when the L2 word processing stage is completed, the reader's attention is shifted to the next word. Fast completion of the L2 stage would yield more time for parafoveal processing of the adjacent word. If there is sufficient time to recognize the word and the saccadic programming has not reached the non-labile stage, a saccade will be programmed to word N + 2 rather than N + 1 (i.e., word N + 1 would be skipped). This line of reasoning would lead to the prediction that foveal processing efficiency is a better predictor of parafoveal processing in reading than parafoveal processing efficiency. Furthermore, foveal processing efficiency measured by word and pseudoword naming indexing more elaborate lexical processing would be better predictors than lexical decision.

Method

Participants

Seventy-four native Finnish speakers (7 male, 67 female, on average 24:9 years of age, SD = 7:3 years, range 17:0–66:6) took part in the experiment. Participants received either study credit or a cinema voucher (value of 10 €) as compensation for their participation. Travel expenses of participants from other cities were also compensated. All participants had either normal or corrected to normal vision. To increase the heterogeneity of the sample, five participants were recruited via an advertisement, where we searched for self-proclaimed excellent readers. Two of them were over 50 years (53 and 66). The rest of the participants were recruited from the university student body (their age range was

17–41 years). Four participants reported a previous diagnosis with mild or moderate dyslexia. One participant reported having strabismus in the left eye and two participants having strabismus in the right eye. The left eye was tracked for those with strabismus in the right eye. The right eye was tracked by default with all other participants.

Apparatus

Eye movements were recorded with an Eyelink1000 system (SR Research, Canada) at 1000 Hz. The stimuli were presented on a BenQ XL2411Z monitor (1920x1080 resolution; frame rate 144 Hz) controlled by an Intel i7-7700 K computer running at 4.20 GHz under Windows 10 environment. Participants were seated 69 cm from the monitor with their head positioned on a chin rest.

Lexical decision, naming and reading tasks

To assess foveal and parafoveal processing efficiency, six different tasks were set up: a lexical decision, word naming and pseudoword naming task to assess foveal processing efficiency and a parafoveal lexical decision, parafoveal word naming and parafoveal pseudoword naming task to assess parafoveal processing efficiency. The words used in the tasks were selected from a Finnish newspaper corpus (Laine & Virtanen, 1999) consisting of 22.7 million tokens. In the parafoveal tasks, the items comprised 5-letter words and pseudowords and in the foveal tasks they ranged between 6 and 8 letters. All words were nouns in the nominative case (i.e., base form), as were the words used as the basis for the pseudoword construction. The pseudowords were constructed by replacing 1–2 letters from a sample of existing words. The created pseudowords were pronounceable and followed the phonotactic rules of Finnish (e.g., vowel harmony present in the Finnish language was not violated).

To assess the orthographic similarity of the words and pseudowords, a mean bigram frequency was calculated for each word and pseudoword. Mean bigram frequencies and mean lemma frequencies for the words are presented in Table 3. Word and bigram frequencies are based on the Turun Sanomat newspaper corpus (Laine & Virtanen, 1999). The items in the lexical decision and naming tasks were presented in Lucida Console font (size 20). In all tasks, a single letter subtended .37 degrees of visual angle.

Foveal lexical decision task

The lexical decision task measures the use of orthographic representations in deciding whether or not the presented stimulus is a word. The task can be successfully performed without explicit word identification. It suffices that a word's orthographic representation is activated to the degree that a word can be separated from a pseudoword, for which no orthographic representation exists.

Table 3
Mean word and bigram frequencies and number of items shown per participant in the lexical decision and naming task.

Task	Mean word frequency / million tokens (SD)	Mean bigram frequency / 1000 tokens (SD)		Number of items shown / participant	
		Words	Pseudowords	Words	Pseudowords
Foveal					
Lexical decision	13.04 (15.16)	7.52 (2.65)	7.16 (2.75)	63	63
Naming	9.50 (12.22)	7.53 (2.57)	7.34 (2.47)	42	42
Parafoveal					
Lexical decision	8.98 (14.66)	6.43 (2.98)	6.38 (2.98)	90	90
Naming	7.39 (7.99)	6.52 (3.04)	6.54 (3.20)	60	60

Note: SD = standard deviation. The items shown to the participants were randomly drawn from a pool of 600 items in both foveal and parafoveal lexical decision. The word frequencies presented here have been calculated from the whole pool of items.

In the foveal lexical decision task, 6–8-letter words and pseudowords were presented backward-masked for identification. Preceding each item, a fixation cross was shown in the center of the screen for 1 s. An item was then shown on the screen for a duration of 60 ms, 40 ms and 20 ms with the center of the word placed in the center of the screen where the fixation cross had been shown. The 60 ms exposure time was chosen as the longest duration, as it has been shown that with 60 ms stimulus exposure reading can proceed normally (no decrement in reading speed or comprehension). This has been demonstrated using the disappearing text paradigm (e.g., Rayner et al., 2003), where each fixated word disappeared 60 ms after the fixation onset on a word. Moreover, we ran a pilot using the exposure times of 80 ms, 60 ms, 40 ms and 20 ms around 60 ms. The distributions of the pilot data suggested that these durations seemed to cover a range of task difficulty from easy to difficult. The easiest block with 80 ms exposure time was used as the practice block (the performance was at ceiling for that block). We later discovered that the shortest exposure time of 20 ms actually produced a floor effect. Thus, this condition was left out of the analyses.

The items subtended 2.2, 2.6 and 3.0 degrees of visual angle for 6-, 7- and 8-letter items, respectively. The stimulus was followed by a mask consisting of capitalized X-letters (equal in width with the shown item) for 30 ms. A blank screen followed the mask, at which point the participant's task was to determine whether the shown item was a word or a pseudoword. The answer was given by pressing a button on the keyboard. If the item appeared too fast to be detected, the participants were advised to press the spacebar (i.e., classify the item as a pass).

Four blocks of items were presented with 80 ms, 60 ms, 40 ms and 20 ms (in this order) exposure times (42 items per block, 126 items in total). As mentioned above, the 80 ms-block was considered a practice block and the 20 ms-condition was not used in the analyses due to a floor effect. Each block contained 21 words and 21 pseudowords. Each block contained the same number of 6-, 7- and 8-letter words and pseudowords (7 items of each length). The order of the items in each block was individually randomized for each participant. The items were drawn at random from a pool of 300 words and 300 pseudowords separately for each participant. This way each participant was shown a random sample of 126 items from the total set of 600 items. A single item could only appear once for each participant.

Foveal naming tasks

The word naming task measures the activation of the word's phonological code. It can be achieved via the direct visual route, in which case the phonological representation needed for naming is activated on the basis of the word's orthographic representation. It is also possible to activate the phonological representation using the indirect route, whereby the word is decoded by applying the grapheme-phoneme correspondence rules. The pseudoword naming task differs from the word naming task in that the task can only be performed using the indirect route.

The foveal naming task was similar to the foveal lexical decision task with few modifications. In the foveal naming task, 6–8 letter words and pseudowords were presented backward-masked for identification. Preceding each item, a fixation cross was shown in the center of the screen for 1 s. An item was then shown for a duration of either 60 ms or 30 ms with the center of the word placed in the center of the screen where the fixation cross had been shown. The exposure times for the naming tasks were selected after running the pilot with the lexical decision task. We then decided to choose exposure time of 30 ms as the shorter duration, as it falls between 20 ms and 40 ms we had chosen for the lexical decision. We chose only two durations for naming, as we did not want to increase the length of the experimental session by adding more task blocks in the experiment. The items subtended 2.2, 2.6 and 3.0 degrees of visual angle for 6-, 7- and 8-letter items, respectively. The target item was then followed by a mask consisting of capitalized X-letters (equal in width with the shown item) for 30 ms. A blank screen followed the mask, at which point the participant's task was to name the item aloud. The experimenter then checked the correct answer from a list and deemed the answer either as correct or incorrect. If the experimenter was unsure about the response, the participant was asked to repeat the answer. If the participant reported having not seen the item at all, the experimenter classified the answer as a pass.

The exposure times of 60 ms and 30 ms were run in separate blocks. Both blocks contained 42 items (84 items in total), 21 words and 21 pseudowords. Both blocks contained the same amount of 6-, 7- and 8-letter words and pseudowords (7 items of each length). A fixed list of items was used in this task, so all participants were exposed to the same items in the same order. Since the foveal naming task was similar to the foveal lexical decision task, no practice block preceded the experimental blocks.

Parafoveal lexical decision task

In the parafoveal lexical decision task, 5-letter words and pseudowords were presented on the screen for 150 ms to the right and left of a fixation cross. Exposure time was selected as 150 ms, as due to saccadic latency it is highly unlikely that the participants would be able to fixate the item even if they tried to do so. Preceding each item, a fixation cross was shown on the screen for 1 s. An item was then shown on the screen randomly either on the right or left side of the cross. This was then followed by a blank screen. The participant's task was to keep their eyes fixated on the cross and make their decision based on what they perceived in the parafovea. Answering (word vs. pseudoword) was done by pressing a button on the keyboard. If the participants were unable to see the item, they were told to press a separate button to classify the item as a pass.

The items were presented randomly on the right and left side of the fixation cross with variable eccentricities. Three blocks of items were shown with eccentricities of 1.33, 1.79 and 2.24 degrees of visual angle (in this order) from the fixation cross to the nearest letter. The eccentricities to the farthest letters were 3.15, 3.61 and 4.07 degrees, respectively. Also, a practice block was shown before the three blocks with an eccentricity of .90 degrees. As the parafovea subtends an area of 5 degrees to each side of the center of the fixation point, all items in each block fell within this range. To select the eccentricities to be tested, we ran a pilot with eccentricity values around 2 degrees of visual angle. Hyönä and Koivisto (2006) had shown that frequent 5-letter Finnish words presented 2 degrees to the right and left of the center fixation point yield above chance performance in lexical decision (they observed accuracies of 62 % and 78 % for words presented to the left and right, respectively). The pilot confirmed that the chosen values did not produce a floor or a ceiling effect.

Each block contained 60 items so that 30 items were shown on the right and 30 items on the left side, each side containing 15 words and 15 pseudowords. The order of items in each block was individually randomized for each participant. The items were drawn at random from a pool of 600 items (300 words and 300 pseudowords) separately for each participant. This way each participant was shown a random sample of 180 items. A single item could only appear once for each participant.

Parafoveal naming tasks

The parafoveal naming task was similar to the parafoveal lexical decision task with few modifications. Five-letter words and pseudowords were presented on the screen for 150 ms to the right and left of the fixation point. Preceding each item, a fixation cross was shown for 1 s. An item was then shown randomly either on the right or left side of the fixation cross. This was then followed by a blank screen. The participants' task was to keep their eyes fixated on the cross and try to parafoveally identify the item and then name it aloud. The experimenter checked the correct answer from a list and pressed a button based on whether the answer was correct or incorrect. If the experimenter was unsure about the response, the participant was asked to repeat the answer. If the participant reported having not been able to see the item at all, the experimenter classified the answer as a pass.

Two blocks of items were shown with eccentricities of 1.33 and 2.24 degrees of visual angle (in this order) to the right and left from the fixation cross to the nearest letter. The eccentricities to the farthest letters were 3.15 and 4.07 degrees, respectively. Thus, all letters of all items fell within the parafovea. Each block contained 60 items so that 30 items were shown on the right and left side, each side containing 15 words and pseudowords. A fixed list of items was used, so all participants were exposed to the same items in the same order. There was no practice block, since the task was similar to the parafoveal lexical decision task.

Reading task

In the reading task, participants read silently for comprehension 8 popular science texts on different topics while their eye movements were registered. Texts were presented in Courier New font (size 20) with a line spacing of 1.08 degrees of visual angle. A single letter subtended 0.46 degrees of visual angle. The texts were short (between 91 and 265 words) expository texts in Finnish dealing with a variety of popular science topics. The texts were adopted from the study of Liversedge et al. (2016). Each text was divided in 2–6 pages, each page containing between 1 and 8 sentences. The text topics were vintage car racing, football, crushing oil from nuts and seeds, sheep farming, ageing effects caused by sugar, tipping culture, health benefits of walking, and wind energy.

Two reading comprehension questions were formulated for each text to encourage the participants to read the texts for comprehension. Comprehension questions were formulated as yes/no questions, for example about whether a subject matter was present in the text or not. On average the participants answered 13.39 out of 16 questions correct (83.7 %).

Procedure

The experiment was run by following good ethical practice with e.g. participants having the possibility to terminate the experiment at any point with no repercussions. Prior to testing, the participants were presented with an informed consent form and were questioned about a possible diagnosis of dyslexia or history of oculomotor problems. Participant's sex and age was also registered. Participants were seated with a distance of 50 cm from the eye to the eye-tracker and 69 cm from the eye to the monitor. A headrest was used to stabilize the participant's head during the tasks.

Testing began by presenting the foveal lexical decision task followed by the parafoveal lexical decision task. Both lexical decision tasks contained written instructions, which the experimenter also explained orally. Answering was done by pressing a key on the keyboard (word, pseudoword or pass). Participants were advised to press the spacebar if the stimulus appeared too fast to be seen at all (i.e., to classify it as a pass). Participants were advised to keep their fingers on the keyboard during the tasks. A written note showing the key mapping was also placed on the table in the participant's view. Both tasks contained a practice block in the beginning to familiarize the participants with the task. In the parafoveal task, the instructions emphasized that the participants should try not to look at the appearing stimulus but to concentrate on keeping their eyes on the fixation cross. Participants were also given the option to take a break after each block. There was also a break between the foveal and parafoveal task.

Next, the participants were presented with the reading task. First, the participants read the instructions, which were also explained orally by the experimenter. The participants were advised to read the texts silently in their own pace in a manner that they would understand the texts. They were told that after each text they would be prompted to answer two reading comprehension questions.

Before starting the reading task, a 9-point calibration procedure was performed to set up the eye-tracker. The calibration error threshold used was a maximum of 1 degree for a single calibration point and a maximum average of.5 degrees of the 9 points. After calibration, each text was presented one page at a time. After reading each page, the participants pressed a button on the keyboard to move to the next page. This was then followed by presenting a drift correction target on the upper left corner of the blank screen. The experimenter then released the next page in view to the participant after their eyes were fixated on the target. This was done in order to guide the participant's first fixation to the beginning of the next page. Participants could reread the text on a single page as much as they wanted but there was no option to return to previous pages.

After the reading task was finished, the participants were presented with the foveal naming task and the parafoveal naming task. Since both of these tasks were similar to the lexical decision tasks, there was no need for practice blocks. In the foveal naming task, participants were instructed to look at the fixation point on the screen and read out loud each presented item. If they were unable to perceive the stimulus, they were advised to report this and the answer was recorded as a pass. The experimenter compared the orally given answer to a list and recorded the answer either as correct, incorrect or as a pass by pressing a button on the experimenter's computer. The parafoveal naming task was done in a similar fashion. As in the parafoveal lexical decision task, in the parafoveal naming task it was emphasized that they should try not to look at the stimulus but to keep fixating the fixation cross at all times. Answers were recorded in the same way as in the foveal naming task.

Variables

Measures of foveal and parafoveal processing efficiency

To assess the performance in the foveal lexical decision task, a mean d' discriminability index was calculated for word detection. This was done using the psycho package in R (Makowski, 2018). Here the hit rate was defined as the rate of success in word detection and the false alarm rate was defined as the rate of false positives in pseudoword detection (i.e. number of pseudowords categorized falsely as words). Items responded by the subjects as a pass (not seeing the item at all) were also categorized as if the participant had made an incorrect classification. The d' index was calculated separately for each block (exposure times of 60 ms and 40 ms) of each participant.

A similar calculation of the d' measure was carried out for the parafoveal lexical decision task. For the parafoveal lexical decision task, the mean d' values were calculated separately for items shown in the right and left visual field in each block (eccentricities of 1.33, 1.79 and 2.24 degrees).

To assess the performance in the foveal naming task, a measure of word naming accuracy and pseudoword naming accuracy were calculated by computing the mean accuracy for the two blocks (exposure times of 60 ms and 30 ms). To assess the performance in the parafoveal naming task, a mean measure of word and pseudoword naming accuracy was calculated separately for the items shown in the right and left visual field in both blocks (eccentricities of 1.33 and 2.24 degrees).

Word-level eye movement measures and predictors

The dependent measures of first fixation duration, gaze duration, probability of refixation, word skipping probability and length of saccade between words were calculated. First fixation duration refers to the duration of the first fixation the word received during the first-pass reading (i.e., the first time when a saccade was launched to the word from a word preceding it in the text). Gaze duration was calculated as the sum of durations of all the fixations the word received between the time it is first entered from a previous word and before it exited to the right or left. Probability of refixation was calculated as a dichotomous variable based on whether a word would receive either only one or more than one fixation during the first-pass reading. Word skipping probability was calculated as a dichotomous variable based on whether or not a word was fixated or skipped during the first-pass reading. For word skipping probability, we calculated only the instances of a skipping saccade launched from a word immediately preceding it in the text. Between-word saccade length was calculated as the distance (degrees of visual angle) between the first fixation of the word and the last fixation of the previous word. This was calculated only for the first-pass reading when the word was first entered from the previous word.

We excluded from the eye-movement data the data for the text titles presented before each text (8 titles shown for each participant). The data on word skipping probability (74882 instances) was filtered as follows. Since the texts were presented in multiple lines, the first word in each line was discarded from the analysis (15.4 % of the whole data). This was done because readers are unable to have a parafoveal preview of these words; thus, skipping line-initial words is not indicative of parafoveal recognition. Instead, typically the saccade launched from the last word of a line towards the first word of the next line may fall short causing the fixation to land on the second word in the line. This is usually followed by a corrective fixation to the first word but causes the first word in line to be considered as skipped on the first-pass reading. Further, all the skipping data for words with frequencies below 2 and above 8 (log/ million tokens) were filtered out (31.9 %), as were the data for words shorter than 4 and longer than 12 letters and compound words containing numerals (19.8 %). Finally, cases where the launch site of the incoming saccade was farther than 7.5 letters (calculated from the beginning of the current word) were discarded from the analysis (1.4 %). After filtering, a total of 51 % (38353 instances) of the data was left to be used in the analysis of word skipping probability.

The data for first fixation duration, gaze duration, probability of refixation and saccade length between words (105820 instances) was first filtered to contain only the data on first-pass reading (82161 instances). From these data, the data for the first word in each line were filtered out (15.5 %), as were the data for the words shorter than 4 and longer than 12 letters and compound words containing numerals (13.1 %) and words with frequencies below 2 and above 8 per million (24.1 %). Further, for between-word saccade length saccades longer than 13 degrees in visual angle and saccades that were moving from right to left were excluded (a total of 20.5 %). This resulted in a dataset of 49,081 instances (59.7 % of the first-pass reading data) to be used in the analysis of first fixation duration, gaze duration and probability of refixation and a dataset of 46,039 instances (56 % of the first-pass reading data) to be used in the analysis of saccade length between words.

Word length in letters and logarithmic lemma frequency per million tokens were used as word-level predictor variables in (G)LLM analyses. Word frequency was calculated from a Finnish newspaper corpus (Laine & Virtanen, 1999). In addition, saccade launch site was entered as a predictor in the analyses of word skipping probability. The launch site of the incoming saccade was defined as the distance (in letters) from the word beginning. It is known that a word is more likely to be skipped, the closer the launch site is (Brysbaert & Vitu, 1998).

Statistical considerations and analysis

First, we inspected the distributions of all the foveal and parafoveal efficiency measures in each block of each task. Due to a floor effect in the distribution of foveal lexical decision at 20 ms exposure time ($M = -.80$, $SD = 1.61$), the block was discarded from further analysis. Further, we discarded the second block (1.79 degrees eccentricity) in parafoveal lexical decision in order to have comparable exposure times and eccentricities between all three tasks. This left us with exposure times of 40 ms and 60 ms for foveal lexical decision, and exposure times of 30 ms and 60 ms for foveal word naming and foveal pseudoword naming. Likewise, this left us with two measures (eccentricities of 1.33 and 2.24 degrees of visual angle) for each visual field (right and left) for all three parafoveal tasks of lexical decision, word naming and pseudoword naming. The remaining 18 foveal and parafoveal efficiency measures were then used as predictors in the Random Forests analysis of each eye movement measure.

We adopted the Random Forests statistical technique previously used by Kuperman et al. (2018) and Matsuki et al. (2016) to simultaneously assess the relative importance of each of the selected foveal and parafoveal efficiency measures in explaining variation in the word-level eye-movement data (see the Supplementary material of S5 in Kuperman et al., 2018 for their original R code and our equivalent R code provided in the OSF repository). It is a non-parametric regression technique that suits well to situations with a large number of collinear predictors, as was the case in the present study.

We ran three Random Forests models for each eye-movement parameter by using the 18 selected processing efficiency measures as predictors in each Random Forest. The three Random Forests for each parameter were constructed by varying the number of simultaneous predictors in each tree of each Random Forest model by changing the value of *mtry* parameter in each run of the model. Following the protocol adopted from Kuperman et al. (2018), the values of the *mtry* parameter were calculated as full integer values between the square root of the number of predictors and the number of predictors divided by 3. This resulted in three Random Forests models for each dependent variable with *mtry* values of 4, 5 and 6. For each Random Forest, the number of decision trees was set as 1000. Mean variable importance scores were then calculated for each predictor from variable importance scores obtained from each tree with a different *mtry* value. The predictors were then plotted in rank order on the basis of their mean variable importance. The predictor variables with highest variable importance were chosen for further analysis for each word-level eye-movement measure. The best predictors were chosen by visually inspecting the variance importance plot of each eye-movement parameter and determining a cutoff point in each plot where a gap was detected in the rank ordered list of importance scores (see Kuperman et al., 2018, for further details). This allowed us to focus on a set of predictors for each eye-movement measure that stood out as the best predictors.

The best predictors were further modelled individually to confirm their capacity to predict eye movements in reading. This was done by calculating a separate (G)LMM model for each selected predictor variable of the eye-movement measures of first fixation duration, gaze duration, probability of refixation, word skipping probability and between-word saccade length. Word frequency and word length were also entered in the models as continuous factors. Separate models were calculated in order not to overcomplicate the fixed effect structures of the models and to avoid issues with multicollinearity. The model selection procedure followed the guidelines outlined by Bates et al. (2015) by fitting each model with a parsimonious random structure supported by the data.

The models for first fixation duration, gaze duration, probability of refixation and between-word saccade length had a fixed effect structure including a three-way interaction of efficiency x word frequency x word length. The random effects structure for these models (before possible pruning) included a random level for items with an intercept and a random level for subjects with random slopes of word frequency and word length. Each model for word skipping probability had a fixed effect structure including two three-way interactions of efficiency x word length x launch site and efficiency x word frequency x launch site. The random effects structure (before possible pruning) was set to include a random level for items with an intercept and a random level for subjects with random slopes of launch site, word length and word frequency.

The analyses were carried out by using the R software (version 4.2.3; R Core Team, 2015). The Random Forests modelling was carried out by using the party package (version 1.3–13; Hothorn et al., 2006; Strobl et al., 2007, 2008). The lme4 package (version 1.1–32; Bates et al., 2015) was used with linear mixed effects and generalized linear mixed effects modeling. The word-level measures of gaze duration and first fixation duration were log-transformed before the analyses. The predictors were centered for each (G)LMM model.

Estimation of statistical power

The participant sample size in the current study compares favorably with those reported in previous literature. On the other hand, the total number of observations (49,081 for fixation duration measures, 46,039 for saccade length and 38,353 for word skipping) exceeds that of almost all previous studies summarized in Tables 1 and 2. The median number of observations in the previous studies is 5,700. Thus, the current study has about 7–8 times more observations than the median of prior studies. There are only two studies (Korinth et al., 2020; Payne et al., 2020) that have more observations than the present study.

To estimate the statistical power in our models, we used a publicly available dataset of Gong and Shuai (2023). They had created composite scores for four individual difference measures: (1) oral comprehension (vocabulary and listening comprehension), (2) decoding (untimed word and nonword pronunciation accuracy), (3) oral reading fluency (reading speed) and (4) print exposure (author and magazine recognition checklist scores). These measures are not directly comparable to the measures used in our study but they provide a rough estimate of the kind of effects individual differences in different components of reading skill can exert. We estimated the power in four different LMMs of gaze duration with a comparable structure to the models in the current study. We formed a separate LMM for four individual difference measures so that each model had a fixed effect structure with a three-way interaction between individual difference measure, word length and word frequency.

We used the simR package in R to extend the number of participants and items to correspond to the sample size of the current study. We then calculated the power with 100 simulations for each of the four different models to detect a three-way interaction (individual difference measure x word frequency x word length) and two two-way interactions (individual difference measure x word frequency and individual difference measure x word length). The average power for the three-way interaction was 80 % (oral comprehension 89 %; decoding 69 %; oral reading fluency 64 %; print exposure 97 %), while the average power for the interaction between the individual difference measure and word frequency was 100 % (oral comprehension 99 %; decoding 100 %; oral reading fluency 99 %; print exposure 100 %) and the average power for the interaction between the individual difference measure and word length was 80 % (oral comprehension 84 %; decoding 72 %; oral reading fluency 88 %; print exposure 76 %). The results suggest that the current sample size yields sufficient power to estimate two-way and three-way interactions between individual difference measures, word length and word frequency.

Results

The means and standard deviations of the performance accuracy for each exposure time (foveal tasks) and eccentricity (parafoveal tasks) of the lexical decision and naming tasks are presented in Table 4. The descriptive statistics for word-level dependent variables are presented in Table 5. All (G)LMM fixed effects estimates are presented in Tables A1 – A5 in the Appendix. Full model descriptions with random effects can be found in the OSF repository.

The data on performance accuracy in the parafoveal tasks compare favorably with the results of Hyönä and Koivisto (2006) and Veldre et al. (2023a). Hyönä and Koivisto presented for 100 ms 4–6 letter frequent Finnish nouns 2 degrees to the left and right of the center fixation point. The conditions comparable to those of the present study (no eye movements allowed) yielded a mean accuracy of 62 % and 78 % for the left and right conditions, respectively, compared to 61 % and 75 % observed in the present study. Veldre et al., (2023a) presented for 100 ms 4–6 letter English words 1 and 2 degrees to the right and left of the center fixation point (Exp. 1A and 3A). The observed accuracies in

Table 4
Means (M) and standard deviations (SD) of foveal and parafoveal performance accuracy in each block of lexical decision (d'), word naming (%) and pseudoword naming (%). Mean accuracy in lexical decision tasks are given in the parentheses.

Task	Exposure time (ms)	Stimulus position	Eccentricity (degrees)	Accuracy M	Accuracy SD
Foveal Lexical Decision (d')	40	Center	–	1.48 (73 %)	1.25
Foveal Lexical Decision (d')	60	Center	–	2.46 (87 %)	.90
Foveal Word Naming (%)	30	Center	–	75.42	23.66
Foveal Word Naming (%)	60	Center	–	94.47	7.88
Foveal Pseudoword Naming (%)	30	Center	–	16.41	19.96
Foveal Pseudoword Naming (%)	60	Center	–	47.62	24.32
Parafoveal Lexical Decision (d')	150	Right	1.33	2.13 (85 %)	.80
Parafoveal Lexical Decision (d')	150	Right	2.24	1.43 (75 %)	.87
Parafoveal Word Naming (%)	150	Right	1.33	91.35	9.15
Parafoveal Word Naming (%)	150	Right	2.24	79.55	14.53
Parafoveal Pseudoword Naming (%)	150	Right	1.33	59.37	20.62
Parafoveal Pseudoword Naming (%)	150	Right	2.24	43.69	21.37
Parafoveal Lexical Decision (d')	150	Left	1.33	1.16 (71 %)	.85
Parafoveal Lexical Decision (d')	150	Left	2.24	.60 (61 %)	1.02
Parafoveal Word Naming (%)	150	Left	1.33	63.15	22.46
Parafoveal Word Naming (%)	150	Left	2.24	47.03	20.82
Parafoveal Pseudoword Naming (%)	150	Left	1.33	28.65	20.99
Parafoveal Pseudoword Naming (%)	150	Left	2.24	22.25	21.83

Table 5
Number of observations (N), means (M) and standard deviations (SD) of the word-level eye movement measures.

	N	M	SD
Gaze duration (ms)	49,081	246	42
First fixation duration (ms)	49,081	205	27
Probability of refixation	49,081	.02	.09
Word skipping probability	38,353	.10	.09
Between-word saccade length (letters)	46,039	9.43	1.49

Note: Means and standard deviations have been calculated from the subject means.

lexical decision were 70 % (Exp. 1A) and 75 % (Exp. 3A) for the 1-degree left condition, 59 % (Exp. 1A) and 64 % (Exp. 3A) for the 2-degree left condition, 84 % (Exp. 1A) and 82 % (Exp. 3A) for the 1-degree right condition, and 72 % (Exp. 1A) and 77 % (Exp. 3A) for the 2-degree right conditions. The accuracies are comparable to those obtained in the present study (see also Exp. 2B of Veldre et al., 2023b). Similarly, the word naming accuracies were also quite comparable between the present study and that of Exp. 2A of Veldre et al., (2023a). The word naming accuracies obtained by Veldre et al. were 93 %, 77 %, 77 % and 47 % for the 1-degree right, 2-degrees right, 1-degree left and 2-degrees left conditions, respectively. The corresponding accuracies observed in the present study are 91 %, 80 %, 63 % and 47 %.

First fixation duration

The Random Forests models for first fixation duration (Fig. 1) indicate that based on the variable importance scores the best predictor variables were foveal pseudoword naming at 60 ms, foveal lexical decision at 40 ms and parafoveal lexical decision on the right side at 1.33 degrees. We ran separate LMMs for these three individual differences variables. Due to the number of models computed, the alpha level for determining statistical significance in the following LMM analyses was Bonferroni-corrected from .05 to .017, which corresponds to $t > 2.39$.

Follow-up LMM analyses of these three measures (Appendix, Table A1) showed a significant main effect of processing efficiency for the model of foveal lexical decision at 40 ms (t = -2.431, B = -.030, SE =.012) and a nearly significant main effect for the model of foveal pseudoword naming at 60 ms (t = -2.230, B = -.000, SE =.001). These effects are depicted in Fig. 2, where it appears that higher scores in foveal pseudoword naming or foveal lexical decision are associated with shorter first fixation durations than lower scores of these variables. It should be noted, however, that the effect of foveal pseudoword naming fell just under statistical significance after correcting the alpha level for multiple comparisons. The main effect for the model with parafoveal lexical decision on the right at 1.33 degrees was clearly non-significant (t =.651). Finally, all models showed significant main effects for word length and word frequency; longer and more infrequent words were associated with longer first fixation durations than shorter and more frequent words.

Gaze duration

The Random Forests models for gaze duration revealed that the best predictor variables based on the scores of variable importance (Fig. 3) are foveal lexical decision at 40 ms, foveal pseudoword naming at 60 ms and foveal word naming at 60 ms. These measures were selected for further LMM analyses. The results of the LMM analyses are presented in the Appendix, Table A2. Based on the number of comparisons, the alpha level for determining statistical significance in the following LMM analyses was Bonferroni-corrected from .05 to .017 which corresponds to $t > 2.39$.

All three LMM models for gaze duration showed a significant main effect of the selected measure of processing efficiency (foveal lexical decision at 40 ms, t = -2.968, B = -.042, SE =.014; foveal pseudoword naming at 60 ms, t = -2.951, B = -.002, SE =.001; foveal word naming at 60 ms, t = -2.668, B = -.006, SE =.002). The nature of all three main effects was such that higher efficiency scores were associated with shorter gaze durations than lower efficiency scores. The model for foveal lexical decision at 40 ms showed an interaction of foveal lexical decision by word length (t = -3.413, B = -.000, SE = -.000). An analogous interaction was observed between foveal word naming at 60 ms and word length (t = -4.240, B = -.001, SE =.000). These interactions are depicted in Fig. 4. As is apparent from the figure, individuals with lower foveal lexical decision scores at 40 ms or lower foveal word naming scores at 60 ms had increasingly longer gaze durations on longer words than those with higher scores. Moreover, the model of foveal pseudoword naming at 60 ms and foveal word naming at 60 ms both showed a similar three-way interaction with pseudoword/word naming, word length and word frequency, where the latter interaction fell just under statistical significance after adjusting for multiple comparisons (foveal pseudoword naming at 60 ms, t = 2.512, B =.000, SE =.000; foveal word naming at 60 ms, t = 2.131, B =.000, SE =.000). The interaction involving pseudoword naming is depicted in Fig. 5. The nature of the interaction is such that individuals with lower processing efficiency scores had increasingly longer gaze durations on longer words than those with higher scores especially when the words were infrequent. An analogous trend was observed for word naming. Finally, all models

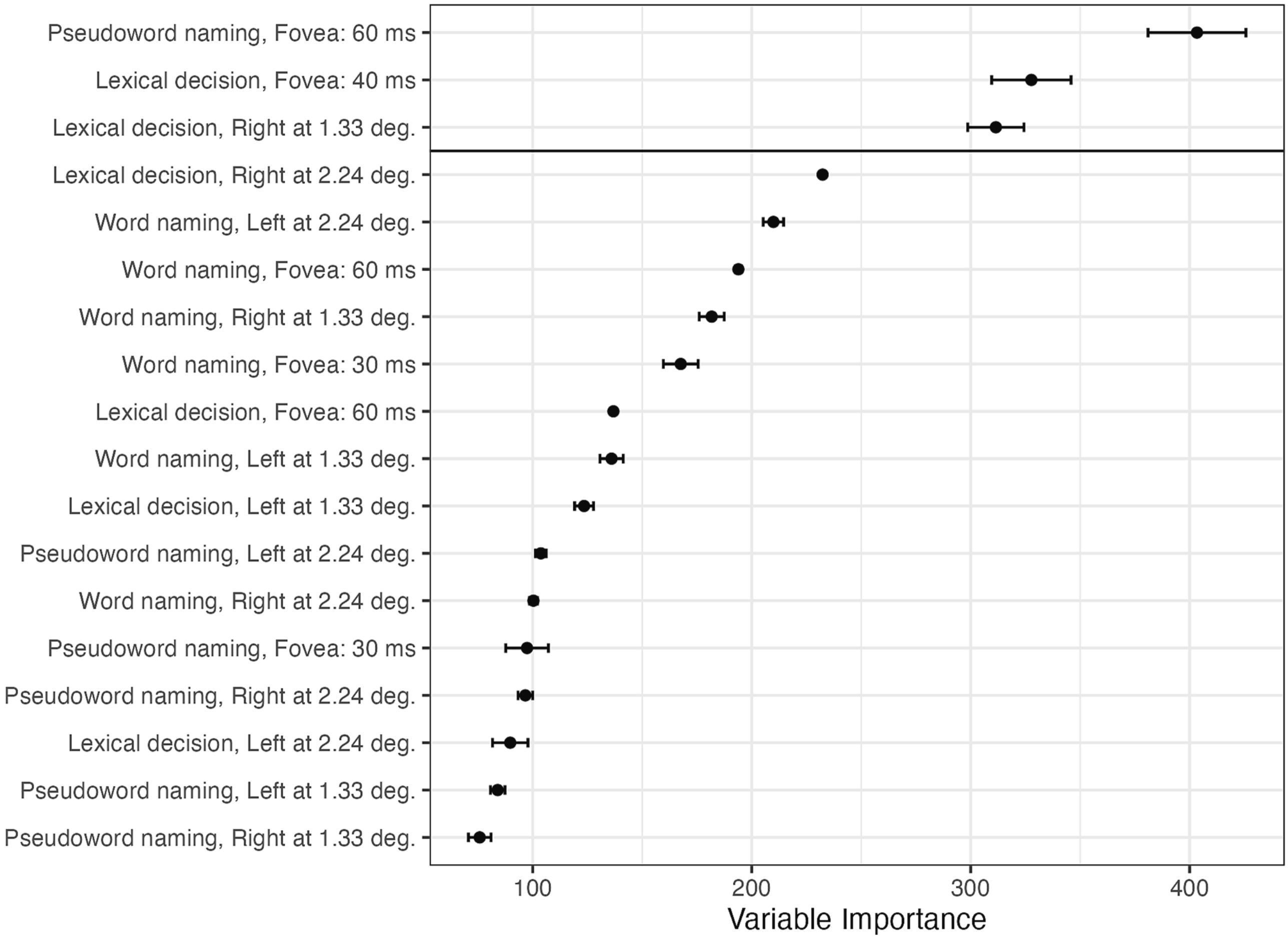

Fig. 1. Relative variable importance estimated by Random Forests models of first fixation duration on the word. The horizontal line indicates the threshold determined by visual inspection for the best predictor variables chosen for further analysis. The error bars indicate the standard error of variable importance calculated from the scores extracted from each run of the Random Forest with a different mtry parameter.

showed significant main effects for word length and word frequency; longer and more infrequent words were associated with longer gaze durations than shorter and more frequent words.

Probability of refixation

The Random Forests models based on variable importance scores for probability of refixation (Fig. 6) indicate that foveal word naming at 60 ms and foveal lexical decision at 60 ms were the best predictor variables. Due to computing two comparisons, the alpha level for determining statistical significance in the following GLMM analyses was Bonferroni-corrected from .05 to .025, which corresponds to $z > 2.24$.

The follow-up GLMM analysis (Appendix, Table A3) revealed a significant main effect of the selected measure of processing efficiency (foveal word naming at 60 ms, $z = -3.383$, OR =.969, SE =.009; foveal lexical decision at 60 ms, $z = -2.888$, OR =.787, SE =.065). The nature of both main effects was such that higher scores in foveal word naming and foveal lexical decision were associated with a lower probability of refixating a word than lower scores. In addition, both models showed a similar two-way interaction of foveal word naming/lexical decision and word length (foveal word naming at 60 ms, $z = -3.339$, OR =.994, SE =.002; foveal lexical decision at 60 ms, $z = -2.737$, OR =.959, SE =.015). These interactions are depicted in Fig. 7. The interaction suggests that the probability of refixation was increasingly higher for longer words for individuals with lower scores in foveal word naming and foveal lexical decision. Finally, both models showed a significant main effect of word length; longer words were associated with a higher probability of refixation than shorter words.

Word skipping probability

The Random Forests models based on variable importance scores for word skipping probability (Fig. 8) indicate that the best predictors include foveal pseudoword naming at 60 ms, foveal word naming at 60 ms, foveal pseudoword naming at 30 ms and foveal lexical decision at 60 ms. Due to computing four comparisons, the alpha level for determining the statistical significance in the following GLMM analyses was Bonferroni-corrected from .05 to .0125 which corresponds to $z > 2.50$.

The follow-up GLMM analyses of these measures (Appendix, Table A4) revealed a significant main effect of the processing efficiency measure in each model (foveal pseudoword naming at 60 ms, $z = 5.324$, OR = 1.038, SE =.007; foveal word naming at 60 ms, $z = 3.361$, OR = 1.083, SE =.026; foveal pseudoword naming at 30 ms, $z = 5.223$, OR = 1.045, SE =.009; and foveal lexical decision at 60 ms, $z = 4.614$, OR = 2.480, SE =.488). These main effects are depicted in Fig. 9. In each main effect, higher processing efficiency scores were associated with higher probabilities of word skipping than lower efficiency scores. As saccade launch site is a significant predictor of word skipping (i.e., words are primarily skipped when the previous fixation is relatively close to the to-be-skipped word), it was also included in the models. Indeed, all models showed a significant main effect of launch site; far saccade launch sites were associated with lower word skipping probabilities than near launch sites. Moreover, the main effect of word length demonstrated that longer words were skipped less often than shorter words. Finally, all models

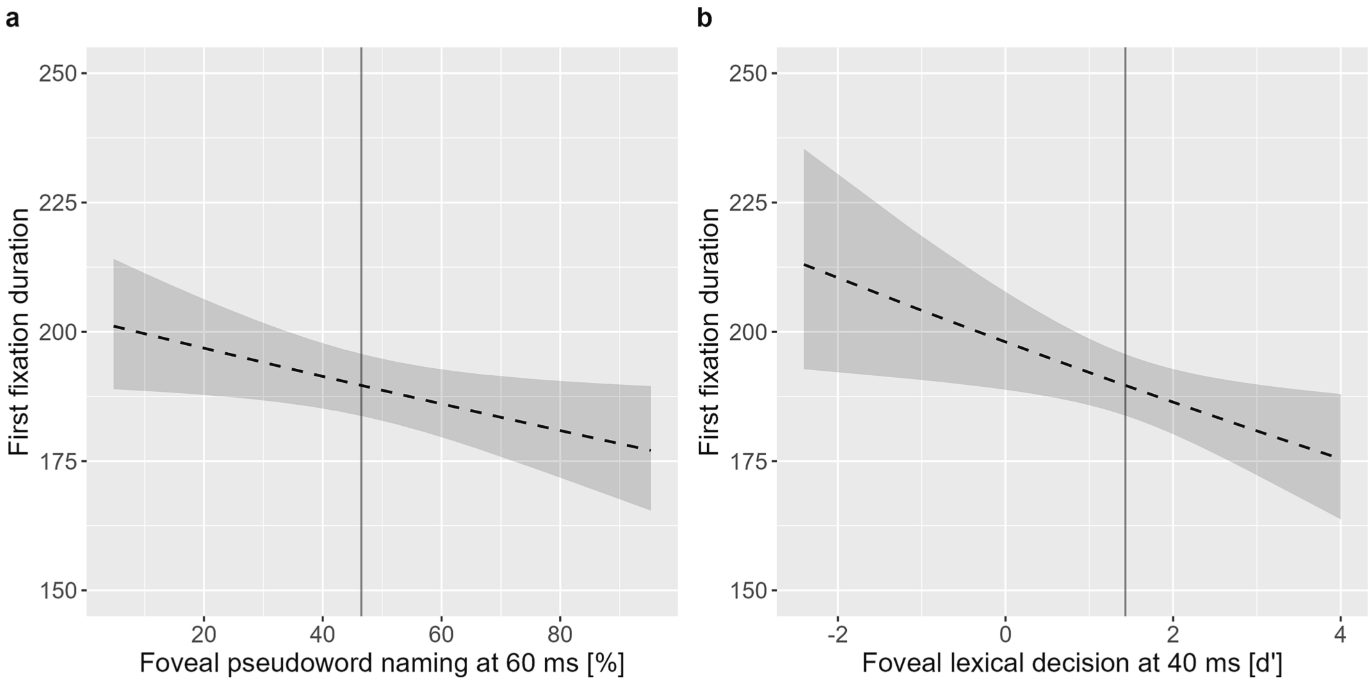

Fig. 2. Estimated marginal LMM means for two different performance accuracy models of first fixation duration as a function of (a) foveal pseudoword naming at 60 ms (panel a); and (b) foveal lexical decision at 40 ms (panel b). Shaded bands represent 95 % CIs based on standard errors. The vertical lines show the point where the main effects of centered variables in x-axis were estimated by the LMMs (i.e., at 46.49 % for foveal pseudoword naming accuracy at 60 ms and at d́=1.43 for foveal lexical decision accuracy at 40 ms).

showed a two-way interaction between saccade launch site and word length; word skipping probability was especially high for short words combined with near saccade launch sites.

Between-word saccade length

Based on the variance importance scores of the Random Forests models for the between-word saccade length (the initial saccade launched to a word from a previous word), the measures of foveal pseudoword naming at 60 ms, foveal pseudoword naming at 30 ms, foveal word naming at 60 ms and foveal lexical decision at 60 ms were selected as the best predictor variables (Fig. 10). Due to computing four comparisons, the alpha level for determining statistical significance in the following LMM analyses was Bonferroni-corrected from .05 to .0125 which corresponds to $t > 2.50$.

The follow-up LMM analysesof the selected measures (Appendix, Table A5) revealed a significant main effect of processing efficiency measure in each model (foveal pseudoword naming at 60 ms, $t = 5.026$, $B = .014$, SE $= .003$; foveal pseudoword naming at 30 ms, $t = 5.521$, $B = .018$, SE $= .003$; foveal word naming at 60 ms, $t = 4.029$, $B = .036$, SE $= .009$; and foveal lexical decision at 60 ms, $t = 4.764$, $B = .364$, SE $= .076$). These main effects are depicted in Fig. 11. Higher foveal processing efficiency scores were associated with longer saccades between words than lower efficiency scores. Also, all models showed a significant main effect of word length; longer words were associated with longer saccades than shorter words.

Summary of results

A summary of all significant effects for the processing efficiency measures selected for further (G)LMM analysis are presented in Table 6.

Discussion

The present study examined if fluency in text reading can be explained by performance accuracy in lexical decision and naming tasks among competent adult readers of Finnish. The predictor tasks measured word and pseudoword recognition efficiency in the fovea and parafovea. Foveal word processing efficiency was assessed by presenting words and pseudowords in the fovea using short exposure durations, while parafoveal word processing efficiency was assessed by presenting the stimuli at varying distances in the parafovea from the center fixation point. These measures were then used to predict word-level eye movement parameters collected during reading. The eye movement parameters were obtained while participants read short expository texts on varying topics. Word-level measures of first fixation duration, gaze duration, probability of refixating a word, probability of word skipping and length of saccade executed between words were calculated from the eye movement data. The first three variables index foveal word processing in reading, while the last two index parafoveal word processing. The non-parametric Random Forests statistical technique was used to estimate the relative importance of the predictor variables in predicting word-level eye movement measures of reading. The method is well suited for the present study, as it enables independent assessment of the relative contribution of multiple collinear predictors.

Foveal word processing efficiency best predicts readers' eye movements

We found that foveal processing efficiency measures were the best predictors of both foveal and parafoveal word processing during reading. Unsurprisingly, individuals who were able to recognize words and pseudowords presented in the fovea with short exposure times read the texts with shorter gaze durations spent on individual words. This finding is in line with previous studies summarized in Table 1. More surprisingly, however, measures of foveal processing efficiency were also the best predictors of parafoveal processing in reading. In other words, word skipping and saccade length were best predicted by foveal efficiency, whereas parafoveal efficiency measures were much poorer predictors of word skipping and saccade length between words.

The finding that parafoveal processing in reading can be predicted by foveal word processing efficiency can be readily explained by the E-Z Reader model (Reichle et al., 1998, 2009) designed to simulate eye

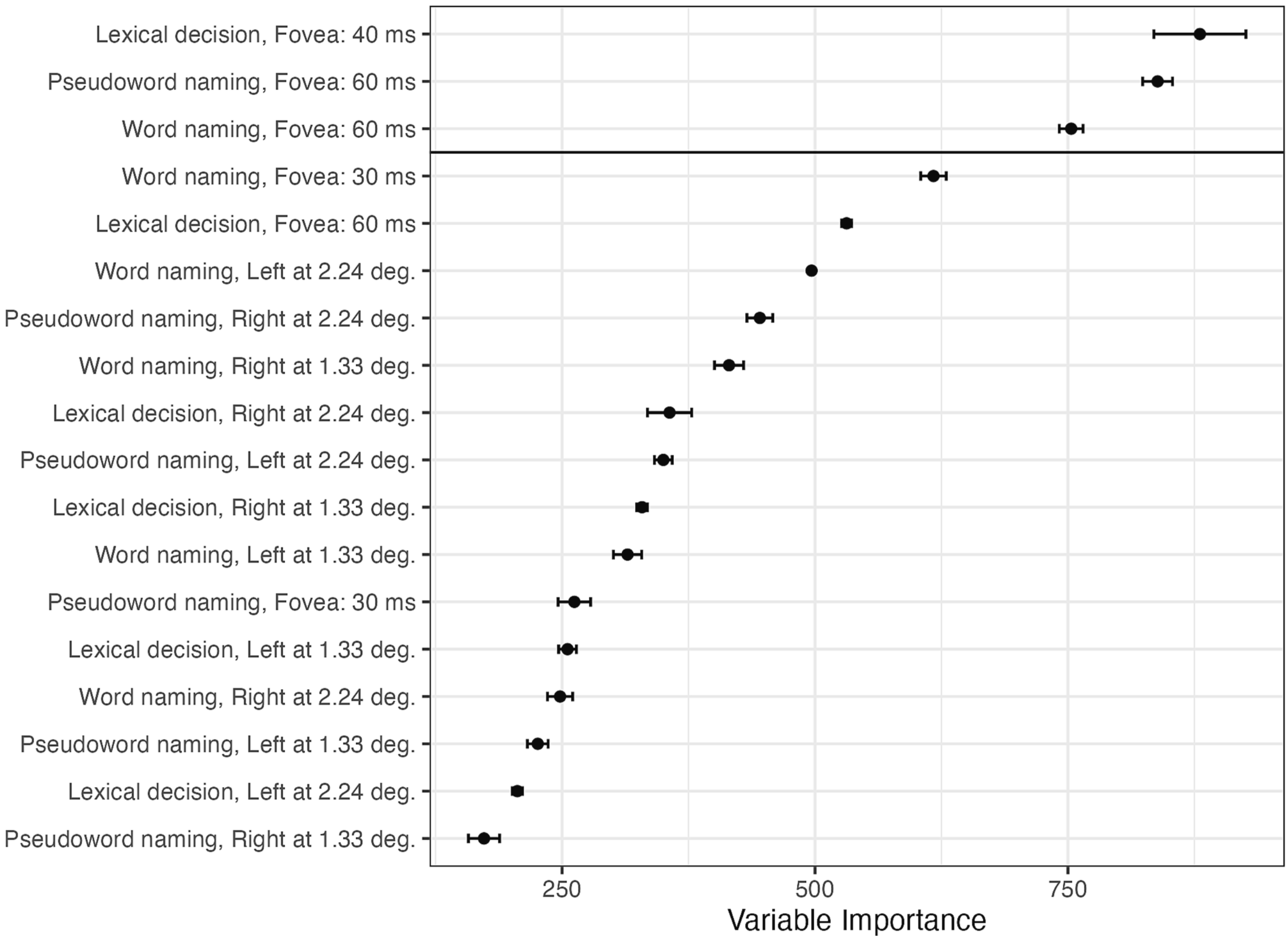

Fig. 3. Relative variable importance estimated by the Random Forests models for gaze duration. The horizontal line indicates the threshold determined by visual inspection for the best predictor variables chosen for further analysis. The error bars indicate the standard error of variable importance calculated from the scores extracted from each run of the Random Forest with a different mtry parameter.

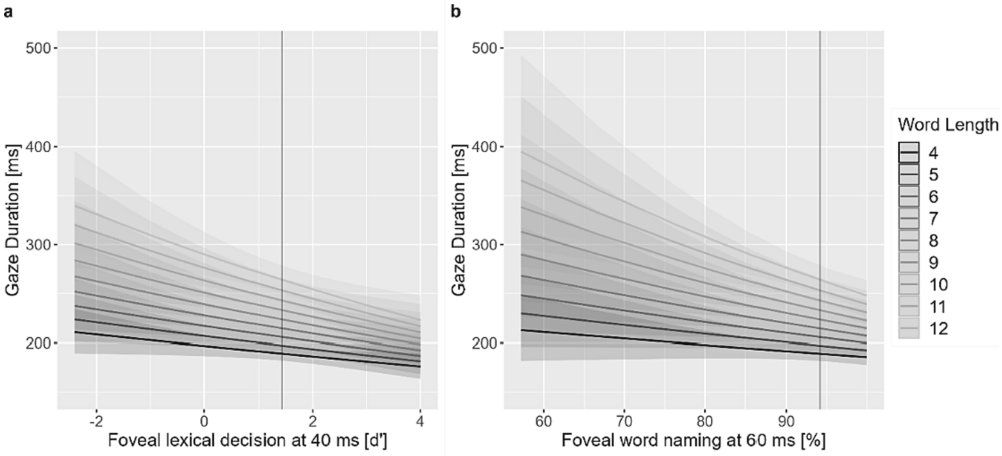

Fig. 4. Estimated marginal LMM means for foveal accuracy models of gaze duration as a function of (a) foveal lexical decision accuracy at 40 ms (d') and word length (panel a); (b) foveal word naming accuracy at 60 ms and word length (panel b). Shaded bands represent 95 % CIs based on standard errors. The vertical lines show the points where the main effect of centered variables in x-axis were estimated in the LMMs (i.e., at d́=1.43 for lexical decision accuracy and at 94.19 % for foveal word naming accuracy). Word length was centered at 7 letters.

movements during reading. According to E-Z Reader, the magnitude of parafoveal processing is dependent on the relative ease of processing the current word. It is known that difficulty in foveal processing can have a negative effect on the amount of information obtained from the parafovea (Henderson & Ferreira, 1990; White et al., 2005). On the other hand, if the currently fixated word can be identified fast, as is the case among readers with efficient foveal word processing ability, attention can shift to the next word and parafoveal processing can then

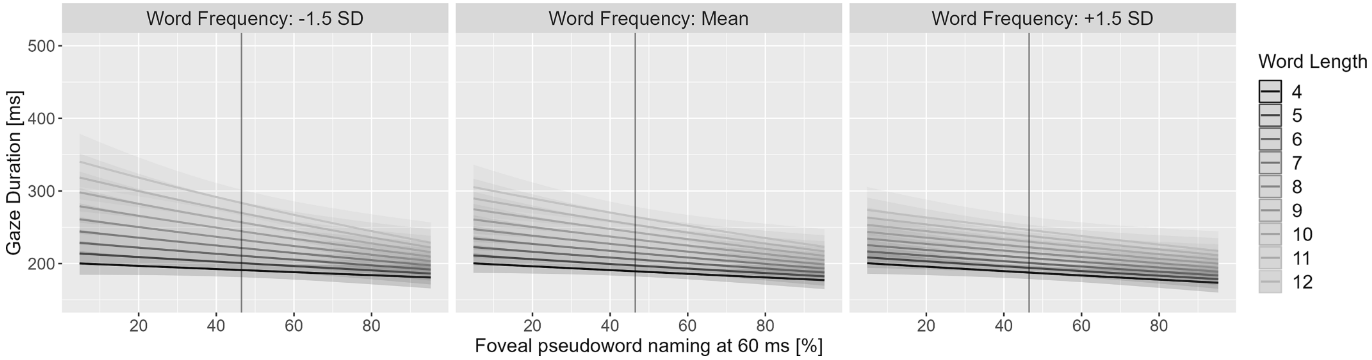

Fig. 5. Estimated marginal LMM means for the model of gaze duration as a function of foveal pseudoword naming accuracy at 60 ms, word length and word frequency. Shaded bands represent 95 % CIs based on standard errors. The vertical lines show the point where the main effect of foveal pseudoword naming accuracy was centered in the LMM (i.e., at 46.49 %). Word length was centered at 7 letters.

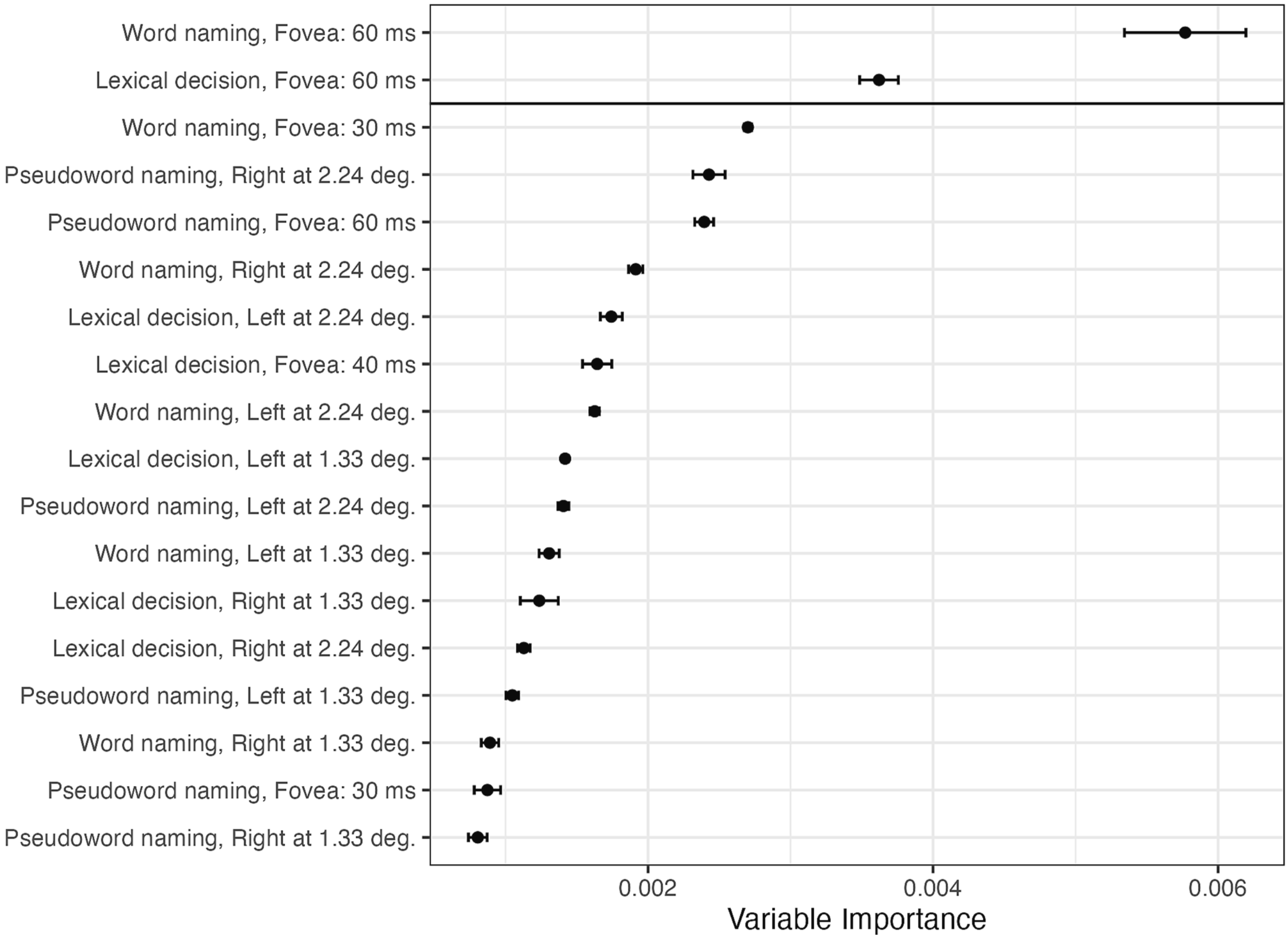

Fig. 6. Relative variable importance for the Random Forests models of probability of refixation. The horizontal line indicates the threshold determined by visual inspection for the best predictor variables chosen for further analysis. The error bars indicate the standard error of variable importance calculated from the scores extracted from each run of the Random Forest with a different mtry parameter.

commence before the next word is actually fixated. If the parafoveal word is recognized during the so-called labile stage of saccade programming, a saccade trajectory can be reprogrammed to skip over the parafoveally recognized word. Naturally, a longer saccade will also ensue. In contrast, when foveal processing is slow, little or no time can be allocated to parafoveal processing resulting in low probability of word skipping.

In sum, the present results suggest that individual differences in perceptual span observed in previous studies (see the summary in Table 2) are not due to more skilled readers having a larger span than less skilled readers. Instead, perceptual span differences are likely to reflect individual differences in the efficiency of dealing with foveally available text information. This is a rather strong statement, which merits further testing in future research. However, it is important to note that we do not wish to argue that individual differences in parafoveal word processing have no power in predicting parafoveal processing in reading (see Table 2). The present results only suggest that individual differences in foveal word processing skills outperform them in

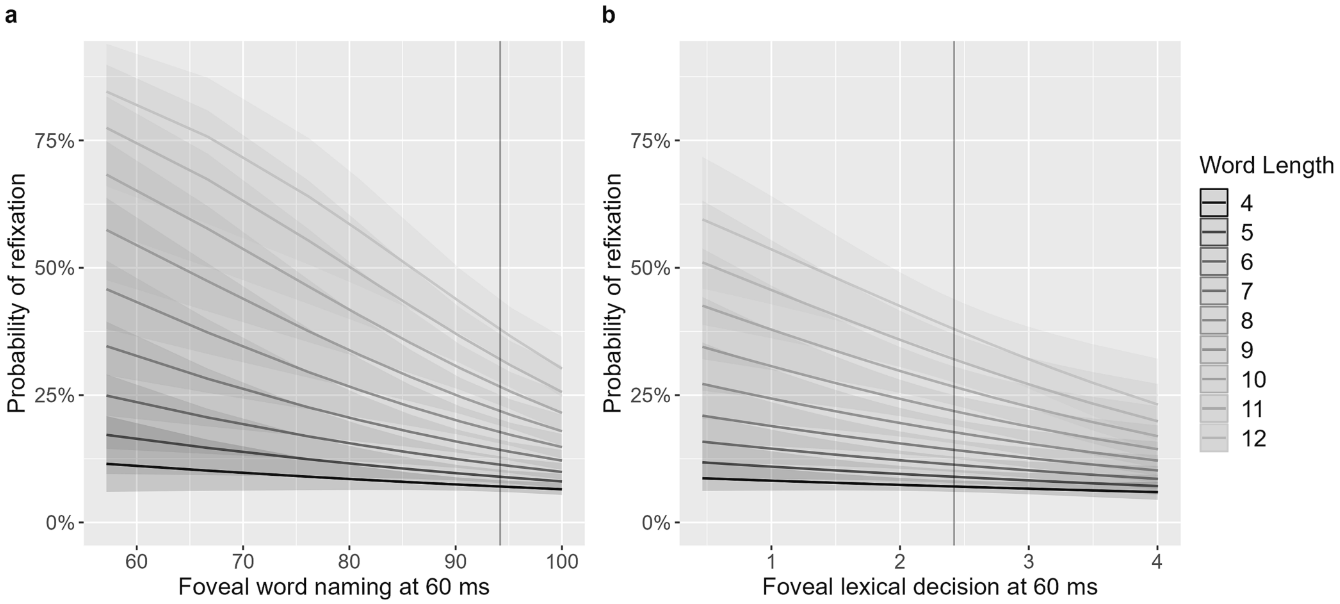

Fig. 7. Estimated marginal GLMM means for the models of probability of refixation as a function of (a) foveal word naming accuracy at 60 ms and word length (panel a); and (b) foveal lexical decision accuracy at 60 ms and word length (panel b). Shaded bands represent 95 % CIs based on standard errors. The vertical lines show the point where the main effects of centered variables in x-axis were estimated by the GLMMs (i.e., at 94.19 % for foveal word naming accuracy at 60 ms and at d'=2.42 for foveal lexical decision accuracy at 60 ms). Word length was centered at 7 letters.

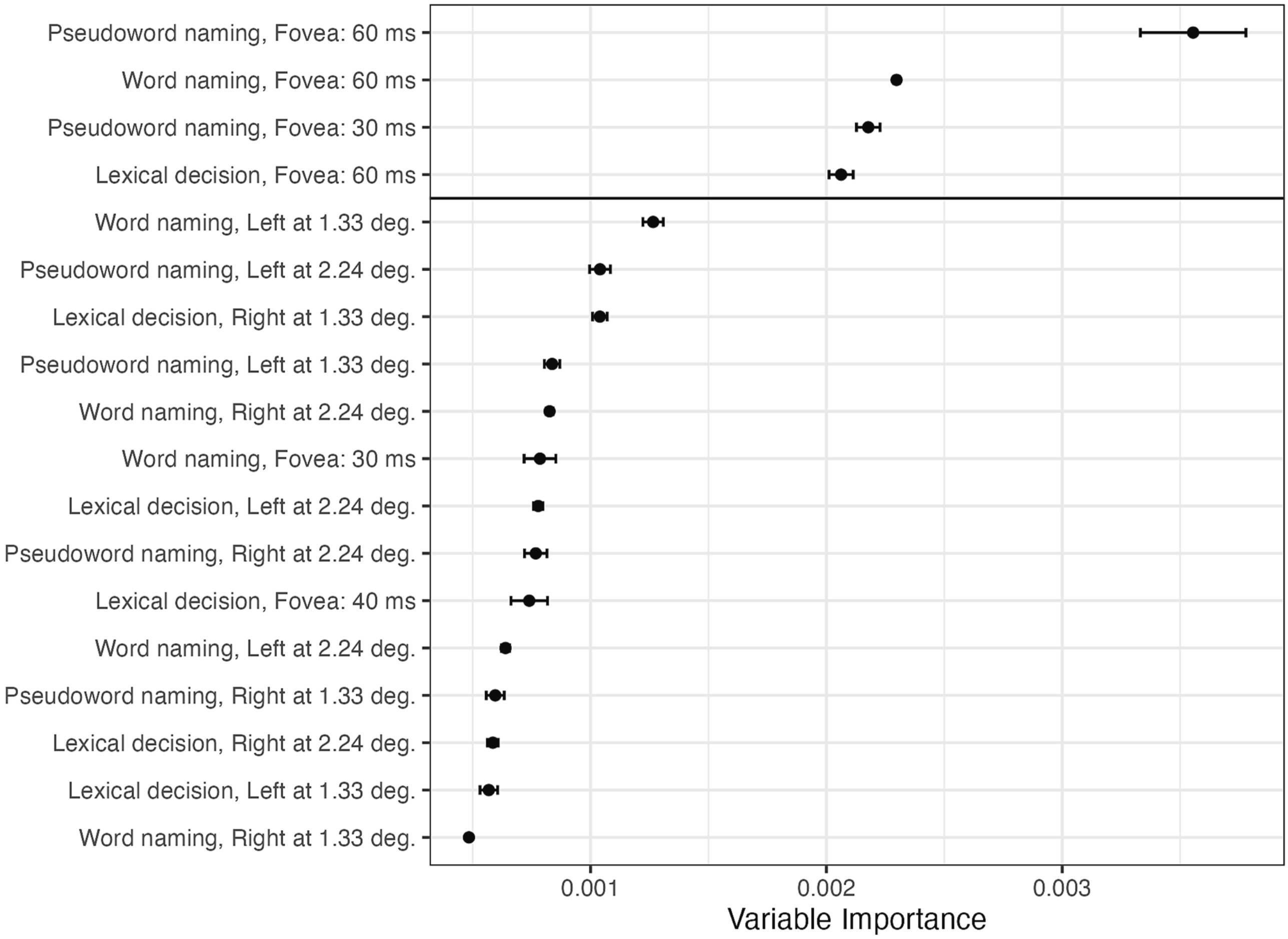

Fig. 8. Relative variable importance for the Random Forests models of word skipping probability. The horizontal line indicates the threshold determined by visual inspection for the best predictor variables chosen for further analysis. The error bars indicate the standard error of variable importance calculated from the scores extracted from each run of the Random Forest with a different mtry parameter.

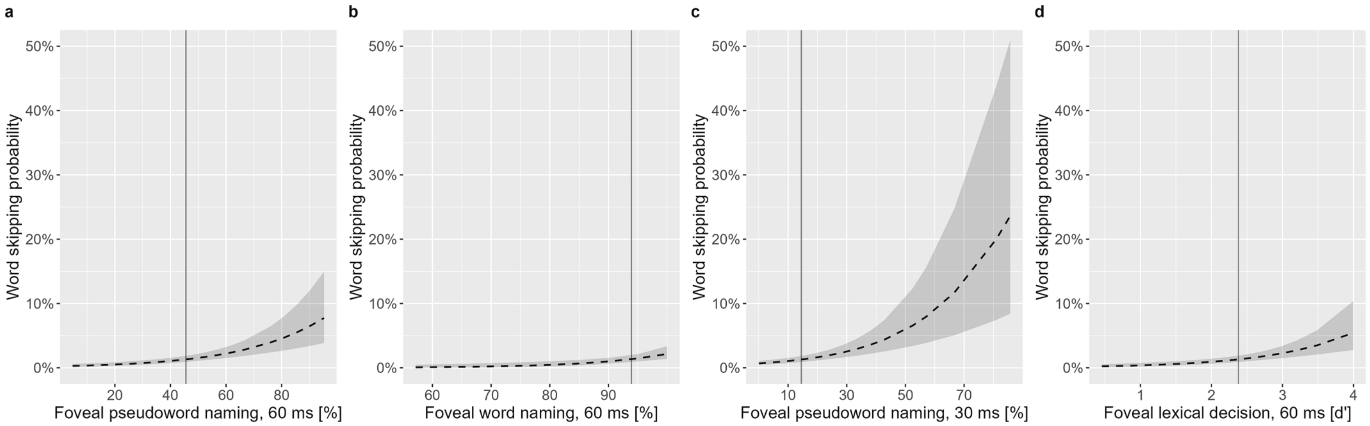

Fig. 9. Estimated marginal GLMM means for the four different models of word skipping probability as a function of (a) foveal pseudoword naming at 60 ms (panel a); (b) foveal word naming at 60 ms (panel b); (c) foveal pseudoword naming at 30 ms (panel c); and (d) foveal lexical decision at 60 ms (panel d). Shaded bands represent 95 % CIs based on standard errors. The vertical lines show the point where the main effects of centered variables in x-axis were estimated in the GLMMs (i.e., at 45.57 % for foveal pseudoword naming at 60 ms, 93.91 % for foveal word naming at 60 ms, 14.51 % for foveal pseudoword naming at 30 ms and at d′=2.38 for foveal lexical decision at 60 ms).

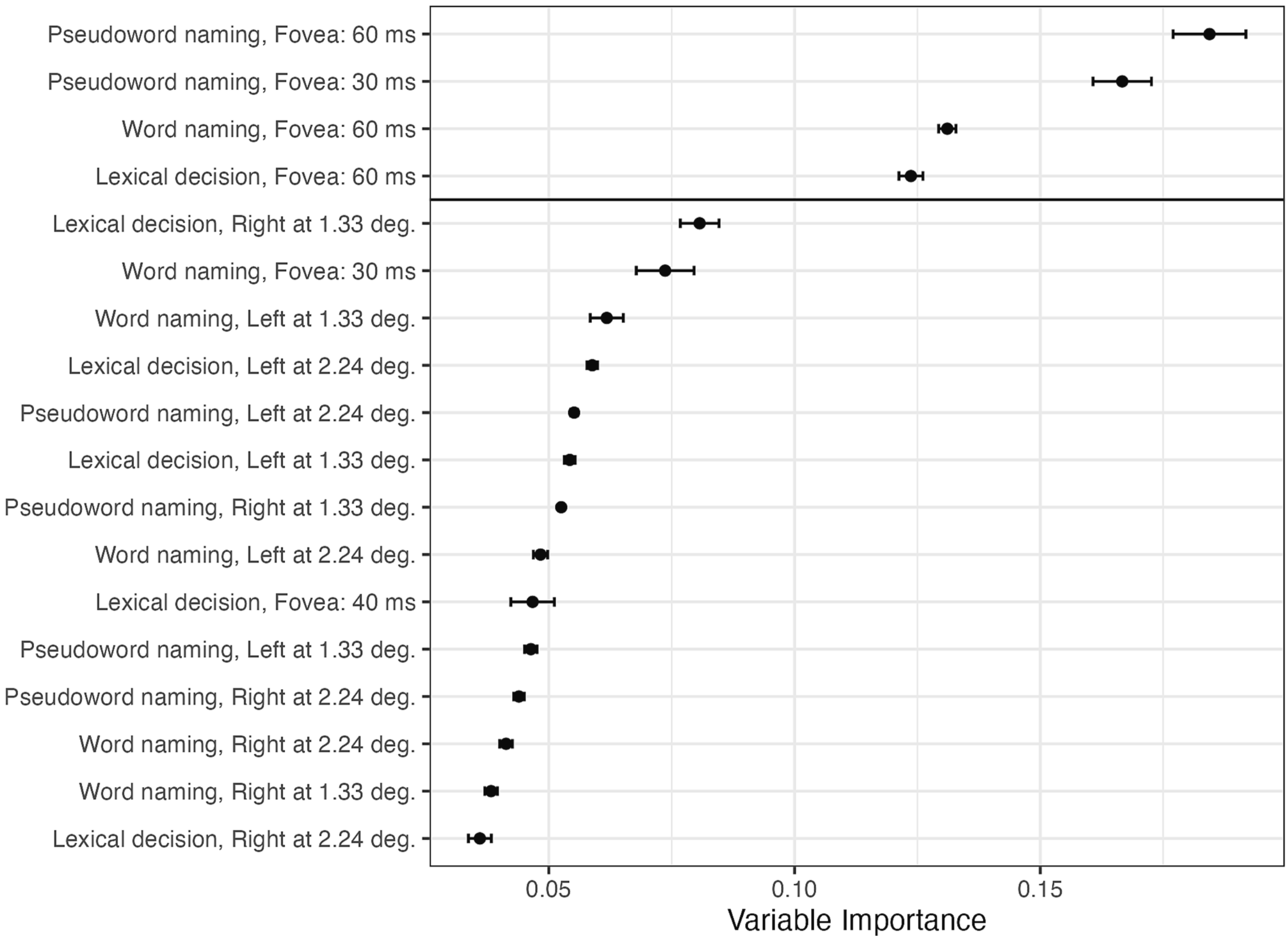

Fig. 10. Relative variable importance for the Random Forests models of between-word saccade length. The horizontal line indicates the threshold determined by visual inspection for the best predictor variables chosen for further analysis. The error bars indicate the standard error of variable importance calculated from the scores extracted from each run of the Random Forest with a different mtry parameter.

predicting parafoveal processing. It is noteworthy that we are not the first to suggest that foveal processing efficiency can predict parafoveal word processing. Veldre and Andrews (2015b) reported results suggesting that precision in orthographic word representations as gauged by spelling ability is associated with success in parafoveal word processing.

Lexical decision predicts early foveal processing in reading

In the Introduction, we argued that the lexical decision task reflects

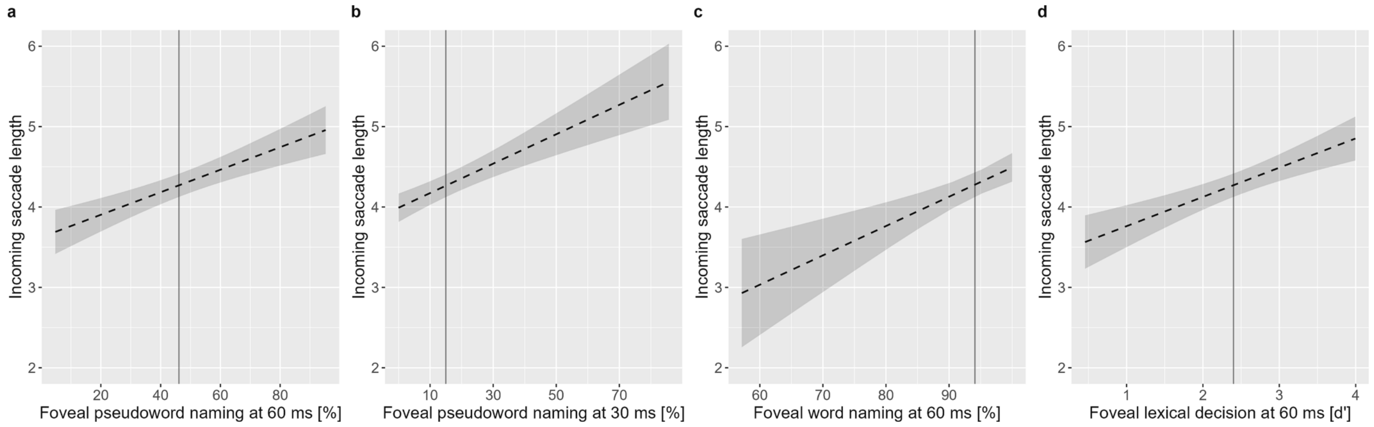

Fig. 11. Estimated marginal LMM means for the four different models of between-word saccade length as a function of (a) foveal pseudoword naming at 60 ms (panel a); (b) foveal pseudoword naming at 30 ms (panel b); (c) foveal word naming at 60 ms (panel c) and (d) foveal lexical decision at 60 ms (panel d). Shaded bands represent 95 % CIs based on standard errors. The vertical lines show the point where the main effects of centered variables in x-axis were estimated in the LMMs (i.e., at 46.13 % for foveal pseudoword naming at 60 ms, 14.98 % for foveal pseudoword naming at 30 ms, 94.1 % for foveal word naming at 60 ms and at d́=2.4 for foveal lexical decision at 60 ms).

Table 6
Summary of significant highest order effects involving processing efficiency in (G)LMMs for first fixation duration, gaze duration, probability of refixation, word skipping probability and between-word saccade length.

Eye-movement variable	Highest order significant effects in (G)LLMs involving processing efficiency				
	Foveal lexical decision		Foveal pseudoword naming		Foveal word naming
First fixation duration	Foveal lexical decision at 40 ms				
Gaze duration	Foveal lexical decision at 40 ms x Word length			Foveal pseudoword naming at 60 ms x Word length x Word frequency	Foveal word naming at 60 ms x Word length
Probability of refixation		Foveal lexical decision at 60 ms x Word length			Foveal word naming at 60 ms x Word length
Word skipping probability		Foveal lexical decision at 60 ms	Foveal pseudoword naming at 30 ms	Foveal pseudoword naming at 60 ms	Foveal word naming at 60 ms
Between-word saccade length		Foveal lexical decision at 60 ms	Foveal pseudoword naming at 30 ms	Foveal pseudoword naming at 60 ms	Foveal word naming at 60 ms

global lexical activation without necessitating explicit recognition. For successful task performance, it suffices that the participant is capable of separating out words from pseudowords. Thus, the task reflects, at least partly, implicit word recognition based on orthographic representations. We speculate that it may reflect the L1 stage of lexical processing postulated in the E-Z Reader model (Reichle et al.,1998, 2009). According to it, L1 is completed when the lexical access is imminent but not complete. The completion of L1 initiates the programming of a saccade to the next word. This theorizing led us to predict that the lexical decision task will be an especially good predictor of early word processing, as indexed particularly by first fixation duration on the word. The present results support the prediction. Lexical decision with 40 ms exposure time was the best predictor of first fixation duration.

Foveal processing efficiency predicts first-pass reading of words

Another key result of the present study is that all our foveal processing measures are good predictors of first-pass reading, as indexed by gaze durations (see Table 6). In other words, individual differences in the efficiency both in orthographic and phonological processing, as indexed by lexical decision and word naming tasks, predict how long readers spend fixating on words during first-pass reading. Also, pseudoword naming indexing decoding ability via the use of grapheme-phoneme conversions is a good predictor of adult participants' reading performance. The latter finding compares favorably with studies conducted in English, where individual differences in spelling ability predict foveal processing in reading (Kuperman & Van Dyke, 2011; Veldre & Andrews, 2016a). Arguably, decoding and spelling ability are related. Readers who can spell words by dictation and recognize spelling mistakes are likely to be also good decoders.

The reliance on the indirect grapheme-phoneme route makes sense in reading Finnish, where there is a perfect one-to-one correspondence between letters and sounds. Thus, anyone who knows how the letters are sounded out can "read" (i.e., decode) Finnish even without knowing a word of Finnish. The use of the indirect route in reading Finnish is also encouraged by almost all content words appearing in running text in morphologically complex forms. For example, there are 14 different case inflections that can be attached to nouns, in addition to possessive suffixes and clitics. Thus, replacing just one letter in the suffix changes the meaning of a morphologically complex noun. For example, the noun phrase "in our house" reads in Finnish "talossamme" (talo = house; -ssa = in; -mme = our), while "from our house" reads "talostamme (talo = house; -sta = from; -mme = our). Moreover, Finnish has a complex verb conjugation system, where single letter replacements change for example the agent performing the action. To sum up, decoding ability is a good predictor of reading a morphologically complex language with shallow orthography like Finnish. Yet, as noted above, it is also linked to reading a morphologically reduced language with deep orthography like English.

Word length modified the effect of individual differences in foveal processing efficiency. Readers who are poorer in fast word processing displayed a stronger word length effect than more efficient readers (see also Gong & Shuai, 2023; Gordon et al., 2019; Kuperman & Van Dyke, 2011). Individual differences were especially noticeable in reading long words. An analogous interaction was also evident in the probability of refixating a word during first-pass reading. In other words, individuals with poorer word recognition ability tended to refixate a word particularly when it was long. The interaction was also evident when individual differences in word recognition skills were gauged by the lexical decision task. Thus, following the above argumentation, this finding suggests that the L1 stage completes slower for long than short words particularly for readers who are poorer in differentiating words from pseudowords with short stimulus exposure times.

Also, word frequency modified the effect of individual differences in decoding ability (pseudoword naming). A similar result has been obtained for English reading (Ashby et al., 2005; Gordon et al., 2019; Kuperman & Van Dyke, 2011, 2013; Veldre et al., 2017). Individual differences in decoding ability were particularly noticeable in reading infrequent words. This makes sense, as decoding skills are especially needed for reading these more difficult words.

Foveal processing efficiency predicts word skipping and saccade length

As noted above, our measures indexing foveal word processing efficiency were also good predictors of parafoveal processing in reading, as indexed by the probability of word skipping and the length of between-word saccades. As is apparent from Table 6, individual differences in all three foveal tasks are good predictors of parafoveal processing in reading. Thus, both orthographic and phonological skills contribute to parafoveal processing. It is important to keep in mind that they are foveal word processing skills, not the parafoveal word processing skills that can predict word skipping.

The finding that pseudoword naming was a good predictor of word skipping and saccade length compares favorably with studies conducted in English. It has been shown that individual differences in spelling ability predict word skipping (Drieghe et al., 2019; Slattery & Yates, 2018; Veldre & Andrews, 2016a; Veldre et al., 2017). As argued above, pseudoword naming and spelling tasks both tap into decoding ability. The finding that foveal lexical decision can predict word skipping suggests that not only decoding skills but also individual differences in words' orthographic processing can modulate the probability of word skipping.

Shortest foveal exposure durations were not consistently the best predictors

In the Introduction, we argued that the shortest durations of stimulus exposure index most efficient word processing. The idea behind the view is that readers who are able to successfully recognize words with very short exposure times have especially good-quality lexical representations that can be activated with minimal stimulus exposure. The present study provided only partial support for this prediction. Of the foveal pseudoword and word naming tasks, the longer exposure duration (60 ms) was a better predictor than the shorter duration (30 ms) except for word skipping and saccade length, for which the shorter duration was also among the best predictors. The result for word skipping makes sense given that there is limited time in processing the parafoveal word while fixating and processing the foveal word. By adopting the theoretical framework of the E-Z Reader model (Reichle et al., 1998, 2009), the processing of the parafoveal word can only commence after the foveal word is recognized. This leaves very little time for parafoveal processing. Readers who are fast in decoding the foveal word, as indexed by pseudoword naming with 30 ms exposure time, have more time for parafoveal processing, which in turn will result in greater skipping probability.

In lexical decision, the shorter foveal exposure time (40 ms) was a good predictor of foveal processing (first fixation duration and gaze duration), while the longer foveal exposure time (60 ms) was a good predictor of parafoveal processing (word skipping and saccade length). It is not obvious why the longer exposure time is a good predictor of parafoveal processing in reading but the shorter one is not. One possibility is that as longer exposure time results in better performance in lexical decision (see Table 4), it reflects individual differences in explicit word recognition required for word skipping.

Conclusions

The present study demonstrates that individual differences in foveal word processing efficiency are better predictors in predicting both foveal and parafoveal word recognition during text reading than differences in parafoveal word processing efficiency. More generally speaking, individual variability in word recognition skills not only determines reading fluency among developing readers but also among more competent adult readers.

CRediT authorship contribution statement

Timo T. Heikkilä: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Nea Soralinna:** Writing – original draft, Investigation. **Jukka Hyönä:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data and R-scripts for all the statistical analyses are available in the Open Science Framework repository (https://osf.io/b43kn/).

Acknowledgments

None.

Appendix

Table A1

LMM fixed effects for three first fixation duration models: (A) word length x word frequency x foveal pseudoword naming at 60 ms; (B) word length x word frequency x foveal lexical decision at 40 ms; and (C) word length x word frequency x parafoveal lexical decision at 1.33 deg to Right. Statistically significant effects ($t > 2.39$) are shown in bold.

Model	Predictor	Estimate	SE	t
A	**Word length (letters)**	**.012**	**.002**	**5.576**
	Word frequency (log)	**-.009**	**.003**	**−2.911**
	Foveal pseudoword naming at 60 ms	-.001	.001	−2.230
	Word length x Word frequency	-.000	.001	-.094

(*continued on next page*)

Table A1 (*continued*)

Model	Predictor	Estimate	SE	*t*
	Word length x Foveal pseudoword naming at 60 ms	.000	.000	1.175
	Word frequency x Foveal pseudoword naming at 60 ms	.000	.000	.209
	Word length x Word frequency x Foveal pseudoword naming at 60 ms	-.000	.000	-.174
B	**Word length (letters)**	**.012**	**.002**	**5.568**
	Word frequency (log)	**-.009**	**.003**	**−2.910**
	Foveal lexical decision at 40 ms	**-.030**	**.012**	**−2.431**
	Word length x Word frequency	-.000	.001	-.091
	Word length x Foveal lexical decision at 40 ms	-.000	.001	-.090
	Word frequency x Foveal lexical decision at 40 ms	-.001	.001	-.522
	Word length x Word frequency x Foveal lexical decision at 40 ms	-.000	.000	-.233
C	**Word length (letters)**	**.012**	**.002**	**5.561**
	Word frequency (log)	**-.009**	**.003**	**−2.908**
	Parafoveal lexical decision at 1.33 deg. Right.(d')	.013	.020	.651
	Word length x Word frequency	-.000	.001	-.102
	Word length x Paraf. lex. dec. at 1.33 deg. Right	.001	.002	.719
	Word frequency x Paraf. lex. dec. at 1.33 deg. Right	.002	.002	1.122
	Word length x Word frequency x Paraf. lex. dec. at 1.33 deg. Right	-.001	.001	−1.397

Note: First fixation duration was log-transformed. SE = standard error. N of subjects = 74, N of items = 565, N of observations = 49081.

Table A2

LMM fixed effects for three gaze duration models: (A) word length x word frequency x foveal lexical decision at 40 ms; (B) word length x word frequency x foveal pseudoword naming at 60 ms; and (C) word length x word frequency x foveal word naming at 60 ms. Statistically significant effects ($t > 2.39$) are shown in bold.

Model	Predictor	Estimate	SE	*t*
A	**Word length (letters)**	**.042**	**.003**	**12.737**
	Word frequency (log)	**-.014**	**.004**	**−3.240**
	Foveal lexical decision at 40 ms	**-.042**	**.014**	**−2.968**
	Word length x Word frequency	-.003	.002	−1.822
	Word length x Foveal lexical decision at 40 ms	**-.005**	**.002**	**−3.106**
	Word frequency x Foveal lexical decision at 40 ms	.001	.001	.747
	Word length x Word frequency x Foveal lexical decision at 40 ms	.001	.001	1.455
B	**Word length (letters)**	**.042**	**.003**	**12.822**
	Word frequency (log)	**-.015**	**.004**	**−3.270**
	Foveal pseudoword naming at 60 ms	**-.002**	**.001**	**−2.951**
	Word length x Word frequency	-.003	.002	−1.817
	Word length x Foveal pseudoword naming at 60 ms	**-.000**	**.000**	**−3.413**
	Word frequency x Foveal pseudoword naming at 60 ms	.000	.000	1.169
	Word length x Word frequency x Foveal pseudoword naming at 60 ms	**.000**	**.000**	**2.512**
C	**Word length (letters)**	**.042**	**.003**	**12.966**
	Word frequency (log)	**-.014**	**.004**	**−3.240**
	Foveal word naming at 60 ms	**-.006**	**.002**	**−2.668**
	Word length x Word frequency	-.003	.002	−1.816
	Word length x Foveal word naming at 60 ms	**-.001**	**.000**	**−4.240**
	Word frequency x Foveal word naming at 60 ms	.000	.000	.499
	Word length x Word frequency x Foveal word naming at 60 ms	.000	.000	2.131

Note: Gaze duration was log-transformed. SE = standard error. N of subjects = 74, N of items = 565, N of observations = 49081.

Table A3

GLMM fixed effects for two probability of refixation models: (A) word length x word frequency x foveal word naming at 60 ms; and (B) word length x word frequency x foveal lexical decision at 60 ms. Statistically significant effects ($z > 2.24$) are shown in bold.

Model	Predictor	Odds Ratio	SE	*z*
A	**Word length (letters)**	**1.298**	**.022**	**15.277**
	Foveal word naming at 60 ms	**.969**	**.009**	**−3.383**
	Word frequency (log)	.959	.019	−2.128
	Word length x Foveal word naming at 60 ms	**.994**	**.002**	**−3.339**
	Word length x Word frequency	.986	.008	−1.693
	Word frequency x Foveal word naming at 60 ms	1.000	.001	.341
	Word length x Word frequency x Foveal word naming at 60 ms	1.000	.001	-.021
B	**Word length (letters)**	**1.298**	**.022**	**15.100**
	Foveal lexical decision at 60 ms	**.787**	**.065**	**−2.888**
	Word frequency (log)	.958	.019	−2.184
	Word length x Foveal lexical decision at 60 ms	**.959**	**.015**	**−2.737**
	Word length x Word frequency	.986	.008	−1.653
	Word frequency x Foveal lexical decision at 60 ms	1.002	.012	.209
	Word length x Word frequency x Foveal lexical decision at 60 ms	1.006	.005	1.338

Note: SE = standard error. N of subjects = 74, N of items = 565, N of observations = 49081.

Table A4

GLMM fixed effects for four separate models of word skipping probability: (A) launch site x word length x foveal pseudoword naming at 60 ms + launch site x word frequency x foveal pseudoword naming at 60 ms; (B) launch site x word length x foveal word naming at 60 ms + launch site x word frequency x foveal word naming at 60 ms; and (C) launch site x word length x foveal pseudoword naming at 30 ms + launch site x word frequency x foveal pseudoword naming at 30 ms; and (D) launch site x word length x foveal lexical decision at 60 ms + launch site x word frequency x foveal lexical decision at 60 ms. Statistically significant effects ($z > 2.50$) are shown in bold.

Model	Predictor	Odds Ratio	SE	*z*
A	**Launch site (letters)**	**.538**	**.027**	**−12.228**
	Word length (letters)	**.396**	**.018**	**−20.499**
	Foveal pseudoword naming at 60 ms	**1.038**	**.007**	**5.324**
	Word frequency (log)	1.096	.046	2.203
	Launch site x Word length	**.936**	**.013**	**−4.870**
	Launch site x Foveal pseudoword naming at 60 ms	1.001	.002	.680
	Word length x Foveal pseudoword naming at 60 ms	1.001	.001	.529
	Launch site x Word frequency	.981	.013	−1.496
	Foveal pseudoword naming at 60 ms x Word frequency	1.000	.001	.243
	Launch site x Word Length x Foveal pseudoword naming at 60 ms	.999	.001	−1.155
	Launch site x Word frequency x Foveal pseudoword naming at 60 ms	1.000	.000	-.741
B	**Launch site (letters)**	**.539**	**.027**	**−12.221**
	Word length (letters)	**.396**	**.018**	**−20.671**
	Foveal word naming at 60 ms	**1.083**	**.026**	**3.361**
	Word frequency (log)	1.095	.046	2.179
	Launch site x Word length	**.934**	**.012**	**−5.104**
	Launch site x Foveal word naming at 60 ms	.997	.007	-.492
	Word length x Foveal word naming at 60 ms	.996	.005	-.761
	Launch site x Word frequency	.978	.013	−1.700
	Foveal word naming at 60 ms x Word frequency	.999	.003	-.284
	Launch site x Word Length x Foveal word naming at 60 ms	.999	.002	-.671
	Launch site x Word frequency x Foveal word naming at 60 ms	1.000	.002	-.099
C	**Launch site (letters)**	**.531**	**.027**	**−12.662**
	Word length (letters)	**.392**	**.018**	**−20.949**
	Foveal pseudoword naming at 30 ms	**1.045**	**.009**	**5.223**
	Word frequency (log)	1.095	.045	2.194
	Launch site x Word length	**.930**	**.012**	**−5.513**
	Launch site x Foveal pseudoword naming at 30 ms	1.003	.002	1.444
	Word length x Foveal pseudoword naming at 30 ms	1.003	.002	1.775
	Launch site x Word frequency	.979	.013	−1.640
	Foveal pseudoword naming at 30 ms x Word frequency	1.000	.001	.188
	Launch site x Word Length x Foveal pseudoword naming at 30 ms	1.000	.001	.169
	Launch site x Word frequency x Foveal pseudoword naming at 30 ms	1.000	.001	-.552
D	**Launch site (letters)**	**.535**	**.027**	**−12.295**
	Word length (letters)	**.395**	**.018**	**−20.498**
	Foveal lexical decision at 60 ms	**2.480**	**.488**	**4.614**
	Word frequency (log)	1.098	.046	2.244
	Launch site x Word length	**.934**	**.013**	**−5.025**
	Launch site x Foveal lexical decision at 60 ms	1.042	.059	.730
	Word length x Foveal lexical decision at 60 ms	1.001	.040	.017
	Launch site x Word frequency	.980	.013	−1.509
	Foveal lexical decision at 60 ms x Word frequency	.987	.025	-.526
	Launch site x Word Length x Foveal lexical decision at 60 ms	.990	.014	-.694
	Launch site x Word frequency x Foveal lexical decision at 60 ms	.989	.014	-.773

Note: SE = standard error. N of subjects = 74, N of items = 565, N of observations = 38353.

Table A5

LMM fixed effects for four models of between-word saccade length: (A) word length x word frequency x foveal pseudoword naming at 60 ms; (B) word length x word frequency x foveal pseudoword naming at 30 ms; (C) word length x word frequency x foveal word naming at 60 ms; and (D) word length x word frequency x foveal lexical decision at 60 ms. Statistically significant effects ($t > 2.50$) are shown in bold.

Model	Predictor	Estimate	SE	*t*
A	**Word length (letters)**	**.093**	**.014**	**6.715**
	Word frequency (log)	.036	.020	1.775
	Foveal pseudoword naming at 60 ms	**.014**	**.003**	**5.026**
	Word length x Word frequency	-.019	.009	−2.055
	Word length x Foveal pseudoword naming at 60 ms	.000	.000	.158
	Word frequency x Foveal pseudoword naming at 60 ms	.000	.000	1.809
	Word length x Word frequency x Foveal pseudoword naming at 60 ms	-.000	.000	-.472
B	**Word length (letters)**	**.093**	**.014**	**6.718**
	Word frequency (log)	.036	.020	1.767
	Foveal pseudoword naming at 30 ms	**.018**	**.003**	**5.521**
	Word length x Word frequency	-.019	.009	−2.049
	Word length x Foveal pseudoword naming at 30 ms	-.000	.000	-.347
	Word frequency x Foveal pseudoword naming at 30 ms	.000	.000	.998
	Word length x Word frequency x Foveal pseudoword naming at 30 ms	.000	.000	.014
C	**Word length (letters)**	**.092**	**.014**	**6.661**

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Table A5 (*continued*)

Model	Predictor	Estimate	SE	*t*
	Word frequency (log)	.036	.020	1.777
	Foveal word naming at 60 ms	**.036**	**.009**	**4.029**
	Word length x Word frequency	-.019	.009	−2.058
	Word length x Foveal word naming at 60 ms	.000	.001	.258
	Word frequency x Foveal word naming at 60 ms	.001	.001	1.239
	Word length x Word frequency x Foveal word naming at60 ms	-.000	.000	−1.234
D	**Word length (letters)**	**.093**	**.014**	**6.716**
	Word frequency (log)	.036	.020	1.770
	Foveal lexical decision at 60 ms	**.364**	**.076**	**4.764**
	Word length x Word frequency	-.019	.009	−2.044
	Word length x Foveal lexical decision at 60 ms	.000	.005	.026
	Word frequency x Foveal lexical decision at 60 ms	.001	.005	.201
	Word length x Word frequency x Foveal lexical decision at 60 ms	-.001	.002	-.572

Note: SE = standard error. N of subjects = 74, N of items = 565, N of observations = 46039.

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