

Literacy skill and intra-individual variability in eye-fixation durations during reading: Evidence from a diverse community-based adult sample

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Abstract

To understand the effects of literacy on fundamental processes involved in reading, we report a secondary data analysis examining individual differences in global eye-movement measures and first-pass eye-movement distributions in a diverse sample of community-dwelling adults aged 16 to 64. Participants ($n = 80$) completed an assessment battery probing verbal and non-verbal cognitive abilities and read simple two-sentence passages while their eye movements were recorded. Analyses were focused on characterising the effects of literacy skill on both global indices of eye-fixation distributions and distributional differences in the sensitivity to lexical features. Global reading measures showed that lower literate adults read more slowly on average. However, distributional analyses of fixation durations revealed that the first-pass fixation durations of adults with lower literacy skill were not slower in general (i.e., there was no shift in the fixation duration distribution among lower literate adults). Instead, lower literacy was associated with greater intra-individual variability in first-pass fixation durations, including an increased proportion of extremely long fixations, differentially skewing the distribution of both first-fixation and gaze durations. Exploratory repeated-measures quantile regression analyses of gaze duration revealed differentially greater influences of word length among lower literate readers and greater activation of phonological and orthographic neighbours among higher literate readers, particularly in the tail of the distribution. Collectively, these findings suggest that literacy skill in adulthood is associated with systematic differences in both global and lexically driven eye-movement control during reading.

Keywords

Literacy; eye movements; reading; language processing; word recognition; intra-individual variability

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Although literacy skill is most typically studied during early reading development, the consequences of literacy are far-reaching throughout the adult lifespan. Indeed, many adults never develop literacy skills that are sufficient to meet the demands of everyday life, including managing health and furthering education and work (Kutner et al., 2007). The 2003 National Assessment of Adult Literacy Survey, based on a comprehensive, nationally representative sample of adult literacy in the United States, found that nearly 11 million adults were considered non-literate and that, even among those considered literate, nearly 30 million more people (~14% of the population) performed below the level of “basic” literacy skills, such as reading simple everyday texts for comprehension. Such stark results are particularly significant in

the context of suggestions that literacy experience may be protective of cognitive and brain functioning in late life (Payne et al., 2012; Stern, 2002; Stine-Morrow et al.,

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2015; Wilson, 2000) and that health literacy is correlated with a number of chronic health outcomes (e.g., Schillinger et al., 2002).

One factor limiting progress in effective literacy instruction for adults stems from the dearth of basic research on the mechanisms underlying reading processes in adults with low-literacy skills. Most of the psycholinguistic research that forms our knowledge of the mechanisms underlying reading comprehension and verbal skill development are focused on either early reading development or variation within highly literate samples of skilled undergraduate readers, which are unlikely to be representative of reading skills in the broader population (Henrich et al., 2010).

For example, studies of eye-movement control over the past 40 years have revealed critical cognitive, motor, and perceptual mechanisms underlying comprehension, with important applications to reading skill development and disorders of reading (see Clifton et al., 2016; Rayner, 2009 for reviews). However, most of this work has been conducted on convenience samples of healthy highly literate college-educated young adult readers, and has similarly focused largely on within-person designs. At the same time, a fast-growing literature on individual differences in eye-movement control in reading has shown that eye-movement characteristics are stable individual differences (Carter & Luke, 2018; Staub & Benatar, 2013) and studies have begun to examine the role that individual differences in working memory (e.g., Traxler et al., 2012), verbal ability (e.g., Kuperman & Van Dyke, 2011), age (e.g., Payne & Stine-Morrow, 2012), and reading development (e.g., Blythe & Joseph, 2011) play in our understanding of skilled reading. Given the strong link between eye-movement control and language processing, and the emerging literature showing stable individual differences in eye movements, it is therefore likely that characterising eye-movement control during reading as a function of literacy skill will help shed light on the cognitive mechanisms underlying literacy development in adulthood. Here, therefore, as an initial step towards understanding how adult literacy skills impact on-line processes of reading comprehension, we examined the effects of literacy skill on global and lexically driven indices of eye-movement control during sentence reading in a community-based sample of racially, educationally, and developmentally diverse adults exhibiting a wide range of reading skill levels.

Eye-movement control in skilled and unskilled readers

Although there is a growing literature on individual differences in eye movements during reading (Radach & Kennedy, 2004; Schroeder et al., 2015), there exist very few studies that have probed the effects of literacy skill in

adulthood. Indeed, the majority of the eye-tracking literature on reading skill has focused on childhood development (Blythe & Joseph, 2011; Reichle et al., 2013). Blythe and Joseph (2011), reviewing the child development literature, highlighted a considerable degree of consistency across studies with respect to how global characteristics of eye-movement control change as children who are learning to read become skilled readers. With increased proficiency, child readers' fixation durations, number of fixations, and number of regressive saccades decrease, such that their eye-movement patterns begin to resemble those of literate college-aged adults (see also Rayner, 1986, 2009). However, few studies have systematically examined literacy-based differences in eye-movement control in adulthood.

There is a growing body of research characterising individual differences in eye-movement control within literate college-aged adults. For example, Ashby and colleagues (2005) examined fixation durations on critical words that varied in word frequency and were embedded in sentences that either were or were not contextually constraining for that word. High-skill readers (based on Nelson–Denny performance, a general assessment of vocabulary and timed discourse comprehension) showed shorter target fixation durations and greater regression rates from the target word compared with less skilled readers. Less skilled readers showed selective increases in the total amount of re-reading time prior to moving forward from the target word. Importantly, Ashby and colleagues found that less skilled readers were differentially slowed in reading unpredictable or low-frequency words compared with highly skilled readers, suggesting a differential sensitivity to lexical features among low-skilled readers. Chace et al. (2005) reported that less skilled readers (also based on Nelson–Denny test performance) showed smaller parafoveal preview benefits and less sensitivity to variation in orthography and phonology in parafoveal vision compared with skilled readers. These findings suggest that the activation of phonological and orthographic representations may be less efficient in less skilled readers. Similarly, Veldre and Andrews (2014, 2015) have examined individual differences in parafoveal word processing as a function of reading and spelling ability. They have shown that more skilled readers gain more information from words to the right of fixation, and are more disrupted by masking of lexical information in parafoveal vision (Veldre & Andrews, 2014). Moreover, they have demonstrated that more proficient readers show greater parafoveal sensitivity to orthographic neighbour frequency compared with less skilled readers. This work has been interpreted as reflecting more efficient lexical activation and higher-quality lexical representations among more proficient readers. Although findings from such studies have revealed individual differences in eye-movement control as a function of reading skill, the generalisability of these results is somewhat

limited as these samples were confined to literate college students, who are selected into university based in part on literacy skill.

To date, one of the most comprehensive examinations of individual differences in literacy skill and eye movements during reading comes from Kuperman and Van Dyke (2011), who conducted a large-scale ($N=71$) investigation of eye-movement measures in sentence reading among young (16–24 years old), non-college-bound English speakers. Participants completed a comprehensive battery of verbal and non-verbal cognitive assessments and read a series of sentences as their eye movements were monitored. Participants who performed better on these assessments showed shorter fixation times in both first- and second-pass reading, as well as a lower likelihood of regressive saccades. This study also showed that effect sizes for individual differences in literacy skill were considerably larger than those of commonly studied lexical variables (e.g., word frequency, word length), indicating that participant-level variance can dwarf and substantially modulate the effects of text-level properties (e.g., word frequency) on eye-movement control in reading. For example, in their study, effects of word frequency were reduced among individuals who scored higher on several measures of reading skill (rapid naming, word identification, and non-word repetition), suggesting facilitated lexical processing among more skilled readers. Similar results have been obtained by Payne and colleagues (2012) in self-paced reading among older individuals who varied in print exposure (a measure of reading experience).

Individual differences in fixation duration distributions

Fluency is a critical component to understanding skilled reading (Wolf & Katzir-Cohen, 2001). Indeed, some eye-tracking studies have suggested that poor fluency is observable not just in overall measures of reading speed, but can also be observed in the earliest measures of word processing—namely, the duration of the first-pass fixations on a word. First-fixation durations and gaze durations are often referred to as early or “first-pass” measures, as they are thought to reflect initial stages of word processing and are often more sensitive to early word recognition processes than to higher-level comprehension processes (see Clifton et al., 2007; Staub & Rayner, 2007, for discussions). Such findings have been taken to suggest that the initial stages of word recognition are slowed among less skilled readers (e.g., Rayner, 2009; Rayner et al., 2003).

To date, however, nearly all of these studies have focused on measures of *average* reading time, which may obscure individual differences in the degree of *variability* in word recognition processes during reading (e.g., Payne & Federmeier, 2017; Payne & Stine-Morrow, 2014; Staub et al., 2010). Indeed, the distribution of word fixation

durations shows a characteristic rightward skew, like most response time (RT) measures (Carter & Luke, 2018; Staub & Benatar, 2013). This tail is ignored in conventional analyses that focus on the average. Thus, when experimental or correlational differences in mean RT are discussed, the interpretation often centres on descriptions of effects on the mean as if they reflect shifts in the entire RT distribution (e.g., a fixed change across all trials or words), rather than a change in scaling or shape of the distribution (Balota & Yap, 2011).

Parametric distributional analyses involve fitting a probability distribution that closely approximates the empirical RT distribution. One distribution, the ex-Gaussian, is a convolution of the Gaussian (normal) and exponential distributions. This distribution has been widely used as a parametric model to describe individual RT distributions (Balota & Yap, 2011; Heathcote et al., 2002, 2004; Van Zandt, 2000). The model contains two parameters from the normal (Gaussian) distribution: μ , the central tendency or location of the distribution, and σ , variability in the modal portion of the distribution. In addition, the model contains a parameter τ , the rate parameter from the exponential component of the distribution, which reflects the degree of rightward skewing in the tail of the distribution. The model is constrained such that the empirical mean is equal to $\mu + \tau$. Therefore, the average RT can be decomposed into one component that is more driven by a *shift* in the distribution (increasing μ , i.e., fixation durations are slower across all words, indicating a shift in the distribution) and a component that reflects an impact on the tail of the distribution (increasing τ , the proportion of extreme fixation durations). Importantly, most prior studies examining the mean alone have interpreted their results as effects on μ —that is, that the manipulation had a uniform effect across all trials, shifting the distribution (see Balota & Yap, 2011, for discussion), an inference that may not hold at the distributional level.

Recently a number of studies have applied the ex-Gaussian distribution to decompose RTs and eye-fixation durations during language processing tasks, including reading sentences. These studies have consistently showed that lexical features and individual difference characteristics exert dissociable effects on different components of the RT distribution (e.g., Carter & Luke, 2018; Payne & Federmeier, 2017; Payne & Stine-Morrow, 2014; Staub et al., 2010; White & Staub, 2012). For example, Staub et al. (2010) showed that a word frequency manipulation produces a shift and a longer tail in fixation time distribution in young literate adults, while White and Staub (2012) showed that reduced stimulus quality produces only a shift in the fixation time distribution.

Trials eliciting extremely slow RTs, in the tail of the distribution, have been argued to index qualitatively distinct underlying cognitive processes. These include lapses of sustained attention (Luke & Henderson, 2013; McVay

& Kane, 2012), halting or disruption of normal word processing (e.g., Staub & Benatar, 2013), or the top-down engagement of attentional control mechanisms (Payne & Federmeier, 2017). Staub and Benatar (2013) examined individual differences in fixation duration distributions in sentence reading, showing that ex-Gaussian fixation duration parameters were stable across individual subjects, and that the overall central tendency (μ) and skew (τ) of the fixation distribution were functionally distinct processes. They argued that τ effects, in particular, may reflect the frequency of processing disruption during reading. Evidence consistent with this claim comes from a recent study examining age-related differences in RT distribution parameters derived from self-paced reading (Payne & Stine-Morrow, 2014). In this study, σ and τ were greater for older than for young readers, although there were no age differences in μ . Importantly, individual differences in verbal working memory (WM) were uniquely related to τ effects in reading, such that older adults with poorer working memory showed an increased frequency of extremely slow RTs during sentence reading.

Our primary goal in the present research was to characterise literacy-based differences in intra-individual variability in word processing through the examination of fixation duration distributions (e.g., Staub & Benatar, 2013). In doing so, we aimed to expand the typical sample that has been used in prior work by collecting data from a diverse, community-based sample of adults varying in age, racial composition, educational level, and literacy skill level. General characteristics of eye movements during reading are well understood for literate college-aged adults. To the extent that patterns of general eye-movement behaviour reflect underlying differences in visual attention allocation, oculomotor control, and comprehension strategies, it is critical to understand how literacy ability impacts such global aspects of reading behaviour.

The impact of lexical variables on eye-movement patterns

Over and above individual differences in global reading behaviour, eye-tracking studies of reading have focused on how lexical influences such as word frequency and word length modulate fixation duration and saccadic behaviour (e.g., skipping, regressions) in literate readers. At the same time, there has been very little work that takes into account potential distributional influences, especially as a function of literacy. Thus, a secondary goal of this study was to conduct an exploratory analysis to characterise the influence of lexical features across the distribution of fixation durations during reading. In literate readers, the word recognition system rapidly decodes the visual signal of printed words and maps that orthographic representation onto its arbitrarily associated lexico-semantic representation. Eye-movement studies have largely focused on word length

and word frequency as the primary lexical features of interest for this process and have shown these measures to be strong word-level predictors of fixation durations in sentence reading (e.g., Clifton et al., 2016; Rayner, 2009). Across many studies, words that are longer and lower in printed frequency show inflated fixation durations relative to shorter and more frequent words, reflecting rapid and direct effects of lexical features on eye-movement control in reading (see Rayner, 1998, 2009; Staub & Rayner, 2007, for reviews).

In addition to features of the specific word, such as its length or frequency of occurrence, models of visual word recognition have increasingly called attention to the representational similarity of the word that is being apprehended to other orthographically or phonologically related “neighbour” words in the lexicon. These neighbours, though not directly observed, nevertheless become activated in the course of word recognition and have a direct effect on word processing (Coltheart et al., 1977; Grainger & Jacobs, 1996; Holcomb et al., 2002). For instance, the N400, an event-related brain potential (ERP) component linked to semantic memory access (Kutas & Federmeier, 2011), is reliably larger in amplitude to words with a greater number of orthographically related neighbours, both during isolated word recognition and reading within sentence contexts (Payne et al., 2015; Payne & Federmeier, 2018, 2019). Furthermore, behavioural studies have found that words with many orthographic neighbours are recognised more quickly (see Andrews, 1997, for a review). This finding of facilitated word recognition has been taken to mean that words with dense orthographic neighbourhoods permit partial activation of multiple words, all of which have excitatory connections to the target. Thus, as neighbourhood density increases, more potential partial paths are activated, leading to more activity in the semantic system (i.e., larger N400s) and greater behavioural facilitation. Studies of the effects of neighbourhood density on eye-movement measures during reading, however, have been limited and the results more mixed, relative to N400 effects and facilitation in visual word recognition. For example, Pollatsek et al. (1999) found that words with large orthographic neighbourhoods were fixated longer, but that these effects occurred on later measures of processing, suggesting a disruptive effect of orthographic neighbours in the context of natural reading. Williams et al. (2006), on the other hand, while not examining neighbourhood density per se, found that words with high-frequency orthographic neighbours showed a facilitated parafoveal preview during reading, suggesting that the existence of salient orthographic neighbours may produce the same sort of facilitated processing as seen in recognition of isolated words.

Similarly, in isolated word recognition tasks, words with many *phonological* neighbours speed lexical decision time (Mulatti et al., 2006; Yates, 2005; Yates et al., 2004;

see Perea, 2015, for a review) and impact the amplitude of the N400 (Carrasco-Ortiz et al., 2017). Phonological neighbourhood density also increases the amplitude of perceptual ERP components such as the P2 (Hunter, 2013). These findings are consistent with the claim that multiple phonologically related representations are activated during word recognition. However, only one study to our knowledge has explored the effects of phonological neighbourhood density on eye-movement control during reading—and again, this was among highly skilled readers. Yates and colleagues (2008) found that target words with large phonological neighbourhoods embedded in sentences showed facilitated fixation durations relative to words with small phonological neighbourhoods.

The development and implicit utilisation of phonological and orthographic representations during silent reading are critical in literacy development (Grainger, 2018; Perea, 2015). At the same time, no work to date has directly examined whether adult literacy skill modulates the effects of orthographic and phonological neighbour activation during silent reading.

The current study

The aims of the current study were twofold. First, we aimed to characterise general eye-movement characteristics and fixation distribution patterns in a community-based sample of adults varying in literacy skill. Recent work suggests that distributional features in reading are stable individual differences (Henderson & Luke, 2014; Staub & Benatar, 2013) and vary as a function of individual difference factors such as working memory and age (Luke et al., 2018; Payne & Stine-Morrow, 2014). Here, we expected that lower literate readers may not vary just in their overall reading rate (i.e., slower reading), but that they may show differential changes in fixation variability in reading (i.e., greater variance and an increased proportion of very slow fixations), consistent with difficulty in the cognitive control of eye movements during reading.

Our second goal was to conduct an exploratory analysis to examine distributional differences in lower and higher literate adults as a function of lexical features including word length, frequency, and orthographic and phonological neighbourhood. Based on the assumption that lexical representations among low-literacy adults are generally poorer in quality, we expected exaggerated effects of word length and frequency (Ng et al., 2019; Perfetti, 2007). To the extent that access to the semantic system is organised by similarity among orthographic inputs and that a key aspect of reading expertise is the development of these orthographic representations (Coltheart et al., 1977; Grainger, 2018), it would be expected that sensitivity to orthographic neighbourhood density would be reduced among less skilled readers, who presumably would not have developed the same level of interconnection in the orthographic network, resulting in a

reduced spreading activation among orthographically similar words during word recognition. Similarly, with respect to the phonological neighbourhood, although low-literate adults would have extensive experience with word phonology from spoken language processing, such phonological representations may not be as strongly activated during silent reading, reflecting a reduced reliance on phonological form among less skilled readers (Anthony & Francis, 2005). Finally, we also examined ordinal word position as a sentence-level predictor. Prior work has shown reliable influences of word position on both fixation durations (Kuperman et al., 2010; Pynte et al., 2008) and self-paced reading (Stine-Morrow et al., 1996). This ordinal position effect is often observed as a decrease in fixation duration or reading time, which has been argued to reflect the accumulation of contextual constraint facilitating processing. Such findings are consistent with electrophysiological work showing robust ordinal position effects on the N400 component of the event-related brain potential (Dambacher et al., 2006; Payne et al., 2015; Payne & Federmeier, 2018; Van Petten & Kutas, 1990), reflecting facilitation from incrementally accruing contexts (see also Payne & Silcox, 2019, for a recent review). However, other work suggests effects of ordinal word position on eye movements may be positive (Pynte et al., 2008) or non-linear (Kuperman et al., 2010). Moreover, an open question in the literature is whether lexical effects (e.g., effects of word frequency) can be modulated by sentence-level features like word position and context (see Kretzschmar et al., 2015; Payne et al., 2015). Because the current study focused on eye-movement control in sentence reading, and because word position can have a strong effect on sentence reading (Kuperman et al., 2010), it was important to account for ordinal position effects when estimating lexical influences across multiple successive words. Moreover, no work to our knowledge has systematically examined literacy differences in word order effects, nor examined distributional changes as a function of word position.

Method

Participants

Participants were community-dwelling adults ($n = 80$) who were diverse in age (16–64 years old), race (73.7% minority), educational attainment (2.0–15.5 years), and literacy skill (2.2–12.5 grade level on the Slosson Oral Reading Task [SORT]; Slosson & Nicholson, 1990; and 2.7–18.0 on the Woodcock–Johnson Reading Fluency task). Table 1 shows means and standard deviations for each individual difference measure used in subsequent analyses (see *Measures* section for more information). Data from this sample based on sentence-final target words as a function of an experimental manipulation of cloze probability have been previously reported by Steen-Baker et al. (2017).

Table 1. Participant characteristics.

Measure	M	SD
1. Age	36.84	14.34
2. Educational level (in years)	11.65	1.9
3. Pattern comparison (speed)	16.81	4.02
4. Letter comparison (speed)	9.62	2.67
5. Vocabulary (Gc)	27.5	8.19
6. Similarities (Gc)	24.45	4.17
7. Block design (Gf)	12.96	5.72
8. Matrices (Gf)	23.245	12.54
9. SORT (RL)	9.54	2.84
10. WJ (RL)	9.02	3.66

Gc: crystallised intelligence; Gf: fluid intelligence; SORT: Slosson Oral Reading Test; WJ: Woodcock–Johnson Reading Fluency; RL: Reading Level.

Measures

Participants completed a broad test battery focusing on characterising individual differences in reading skill, crystallised intelligence (Gc), fluid intelligence (Gf), and psychomotor speed.

Reading skill. The Slosson Oral Reading Test (SORT) is a word-identification task in which the subject is presented with a series of 12 grade-level lists of words and the task is to pronounce the words as accurately as possible (Slosson & Nicholson, 1990) with no time limit. The number of correct items corresponds to a grade-level estimate of reading ability. In the Woodcock–Johnson Reading Fluency task, participants are presented with a list of 98 simple sentences and are required to silently read and determine the truth value for as many as possible within 3 min (Schrank et al., 2014). This is a measure of fluency in executing the coordinated processes that are needed to understand a simple sentence. The number of items correct has been normed against a grade-level estimation of reading skill. Literacy level for each subject was derived from the average of grade-level estimates of the Woodcock–Johnson task and the SORT, which represent the constructs of reading fluency and word recognition, respectively.

Intelligence. Fluid and crystallised intelligence were measured with The Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1981). Assessments of fluid intelligence (Gf) include block design (i.e., arranging blocks to match a prompt within a particular time limit) and matrix reasoning (i.e., multiple choice pattern-completion task), and assessments of crystallised intelligence (Gc) probe vocabulary knowledge and the ability to articulate similarities between objects.

Psychomotor speed. Psychomotor speed was assessed with the letter and pattern comparison tasks (Salthouse, 1996). The letter-comparison task requires participants to compare

strings of letters and indicate whether they are the same or different within a time limit of 30s. Similarly, the pattern comparison task requires participants to make judgements on two abstract line drawings. For each task, participants attempt two trials, and the score corresponds to the mean number of items correct from the two trials.

Materials and stimulus characteristics

Participants read a total of 60 congruent two-sentence passages, with a Flesch-Kincaid reading level of 4.1 or below (e.g., “The lot was so full that the driver didn’t think he would find a place to park. He knew he should have gotten there earlier.”). Analyses were conducted on all open-class (typically defined as “meaning-bearing”) words within the sentences, including nouns, verbs, adjectives, and derived adverbs (-ly adverbs) (e.g., Payne et al., 2015, 2018). Following the dichotomous assignment of words in Van Petten and Kutas (1991), words of ambiguous class were assigned to a closed-class category. Analyses here were focused across the entire sentence context, from the second word through (but not including) the sentence-final word. Sentence-initial and final words were excluded to ensure a more visually and cognitively homogeneous set of stimuli, as fixations on sentence boundary words would be expected to differ in a number of ways, including the availability of parafoveal information from flanking words (Schotter et al., 2012), as well as due to differences in fixation durations likely driven by oculomotor planning (Kuperman et al., 2010) and sentence-final wrap-up effects (Kuperman & Bresnan, 2012; Payne & Stine-Morrow, 2012). Moreover, by excluding the sentence-final word, the data presented in the current article are independent of the data previously reported in Steen-Baker et al. (2017), which focused only on sentence-final word processing. This led to a total of 87,106 observations (words × subjects) in the final data set. A comprehension question followed each two-sentence passage, with equal numbers of YES and NO answers. Questions were designed to probe information from different parts of the sentences or to require simple inferences. See Steen et al. (2017) for results on the off-line comprehension questions.

For the distributional lexical analyses (see below for more details), the following lexical characteristics were estimated from the stimulus materials: Word frequency, word length, orthographic and phonological neighbourhood, and word position (WP). Table 2 contains descriptive statistics on stimulus characteristics. Word length was measured in number of characters. Word frequency (log transformed) was derived from the Hyperspace Analog to Language (HAL) norms from the English Lexicon Project (see Balota et al., 2007). Orthographic neighbourhood (ON) sizes were derived from the Orthographic Levenshtein Distance 20 (OLD20) measure (Yarkoni et al., 2008) from the English Lexicon Project. OLD20 reflects the mean distance (in

Table 2. Lexical characteristics of open-class words used in quantile regression analyses.

Lexical characteristic	<i>M</i>	<i>SD</i>	Minimum	Maximum
1. Word length (in characters)	3.73	1.75	1	12
2. Word frequency (log HAL)	13.32	2.62	1.79	16.96
3. Orthographic N (OLD 20)	1.53	0.44	1	4.7
4. Phonological N (PLD 20)	1.37	0.5	1	5.55
5. Ordinal word position	9.1	5.6	1	27

HAL: Hyperspace Analog to Language; OLD: Orthographic Levenshtein Distance; PLD: Phonological Levenshtein Distance.

number of steps) from each word to the 20 closest Levenshtein neighbours in the lexicon. Levenshtein distance (Levenshtein, 1966) is the minimum number of substitutions, insertions, or deletion operations required to turn one word into another. Thus, words with higher OLD20 scores are considered orthographically sparse (have relatively fewer neighbours), whereas words with lower OLD20 scores are considered orthographically dense (have relatively more neighbours); note that this measure is, therefore, negatively correlated with traditional measures of orthographic neighbourhood, such as Coltheart's *N*. Similarly, phonological neighbourhood (PN) was measured as Phonological Levenshtein Distance 20 (PLD 20) (Suárez et al., 2011), which computes the mean phonemic edit distance among the closest 20 neighbours for each word. Like OLD20, PLD20 scores are thus negatively correlated with phonological neighbourhood density.

Procedure

The entire session lasted approximately 2 hr. First, participants provided information about background and health and were then administered the test battery. Afterward, they completed the eye-tracking reading task. Participants read the sentences while their eye movements were monitored using an Eye-Link 1000 Plus desktop-mounted eye tracker (SR Research Ltd., Ottawa, ON, Canada), sampling at a rate of 1000Hz. Sentences were presented in white 20-point Courier New font on a black background on a 17-inch Dell monitor set to 1024 × 768 resolution, and a refresh rate of 85Hz. Participants were seated approximately 70 cm from the monitor (1.73 characters subtended 1° of visual angle). Participants placed their head in a chin rest to minimise head movements. The experimenter aligned and calibrated the tracker to one of the subject's eyes (starting with the right eye and moving to left eye, if necessary). When properly calibrated, the participant could initiate each trial by pressing a button on a response pad. In addition, a fixation check was presented between each trial to verify that the tracker remained properly calibrated. In cases where the calibration was lost, the tracker was completely recalibrated before proceeding. Participants were presented with a set of eight practice texts for reading and to answer comprehension questions prior to the experimental items.

Eye-movement measures and data analysis

First, we report global analyses on fixation and saccade behaviour. We report two average measures of first-pass word fixation durations: first-fixation durations (duration of the first fixation on each word) and gaze durations (i.e., first-pass reading times: the sum of all first-pass fixations on each word before moving off the word), as well as total reading time (sum of all fixations on each word). In addition, we report an estimate of reading rate in words per minute in order to facilitate a descriptive comparison in gross reading speed between this sample and prior work (e.g., Brysbaert, 2019). Three saccade-based measures are also presented: the probability of regressing (i.e., that the eyes move left to an earlier word from the target), the probability of skipping (the proportion of words skipped during first-pass reading), and the probability of refixation (i.e., that a word was fixated more than once during first-pass reading). Global fixation and saccade-based measures (regressions, skipping) were analysed via general(ized) linear mixed models. For the fixation-based measures, linear models were fit and for the saccade-based measures, logit mixed models were fit. For linear models, degrees of freedom are approximated using the Satterthwaite method. Random intercept terms were included for subjects and words. Literacy level was included as a continuous linear effect and the following covariates were included in all models to control for individual differences: psychomotor speed, crystallised intelligence (*Gc*), fluid intelligence (*Gf*), and age.¹ All individual difference variables were standardised to facilitate effect size interpretation.

To better characterise the first-pass reading effects, we used a distributional analysis to decompose first-fixation durations and gaze durations. For these analyses, the ex-Gaussian distribution was fit separately to each individual subject's single-word first-fixation durations and gaze durations, using a bootstrapped maximum likelihood approach via the *retimes* package in R (Massidda, 2015). Bootstrapped resampling of the data ($n=500$) was used to identify each distribution parameter, estimated separately for each participant (see Van Zandt, 2000). The ex-Gaussian models converged normally for each participant. Linear regression models were then fit separately on each ex-Gaussian parameter, with reading level as a predictor, controlling for individual differences in psychomotor speed, crystallised intelligence (*Gc*), fluid

Table 3. Means and standard deviations of global reading measures for higher and lower literacy groups.

Measure	Lower literacy		Higher literacy	
	M or proportion	SD	M or proportion	SD
1. First-fixation duration (ms)	239	98	219	83
2. Gaze duration (ms)	309	172	257	131
3. Total reading time (ms)	365	339	280	282
4. p(Regress)	0.19	0.39	0.16	0.37
5. p(Skip)	0.42	0.49	0.43	0.5
6. p(Refixate)	0.26	0.44	0.16	0.37
7. Reading rate (wpm)	179.8	78.7	228.1	94.3

intelligence (Gf), and age, using the `lm()` function in R (see Supplementary materials for non-parametric Vincentile plots, which confirm the ex-Gaussian results presented below). All individual difference variables were standardised to facilitate effect size interpretation.

Our second aim was to conduct an exploratory lexical analysis to examine the impact of lexical variation on eye-fixation distributions during reading. We adopted a repeated-measures (RM) quantile regression approach (e.g., Risse & Kliegl, 2014; Schotter & Leininger, 2016) to examine the impact of lexical features across the entire distribution. To reduce the number of statistically dependent measures in this exploratory analysis, analyses are presented for gaze durations only, as this measure reflects a more complete first-pass measure of word recognition compared with first-fixation durations. It is important to note that because gaze durations include first-pass refixations, they have been argued to reflect a more intermediate stage of word processing compared with first-fixation duration and may reflect some degree of interference in normal processing (Clifton et al., 2007; Payne & Stine-Morrow, 2012). Quantile regression models can be used to estimate the effect of a set of predictor variables across conditional quantiles of a response variable. Quantile regression functions were fit using the `quantreg` package in R (Koenker, 2005). Following the method described in Risse and Kliegl (2014), quantile regression models were estimated across deciles of the fixation distribution separately for each participant (see also Payne & Stine-Morrow, 2014; Stine-Morrow et al., 2008, for similar approaches to RM linear regression). For all reported test statistics, α was set at .05.

Results

Global fixation measures

Table 3 presents the means and standard deviations for each reading measure separately for higher literate adults (above the median reading grade level of 9.5) and lower literate adults (below the median reading grade level of 9.5) as a descriptive way of visualising literacy differences

and comparing overall reading measures to the prior literature. Note however that for all statistical analyses below, literacy level is treated as a continuous covariate.

Average fixation measures. Literacy level emerged as the only significant predictor of average word first-fixation durations, $b = -4.39$ ms, $SE = 1.54$, $t(72.84) = -2.84$, $p < .01$, gaze durations, $b = -8.81$ ms, $SE = 2.39$, $t(72.74) = -5.10$, $p < .001$, and total reading times, $b = -19.99$ ms, $SE = 5.36$, $t(72.99) = -3.73$, $p < .001$, such that more skilled readers showed overall faster average word reading times. No other individual difference measures uniquely predicted word fixation duration measures. Literacy level significantly predicted overall reading rate, $b = 29.23$ wpm, $SE = 9.23$, $t(72.97) = 3.16$, $p < .01$, such that higher literate adults showed faster reading rates. In addition, individual differences in processing speed showed a nonsignificant trend in predicting reading rate, $b = 15.53$ wpm, $SE = 8.52$, $t(72.97) = 1.82$, $p = .07$.

Saccade-based measures. For regressions, literacy level emerged as the only significant predictor ($b = -1.63$, $SE = .06$, $z = -2.38$, $p < .05$), such that more skilled readers regressed less frequently overall. For word skipping, a different pattern emerged. Fluid ability (Gf) was a significant predictor ($b = -.23$, $SE = .09$, $z = -2.55$, $p < .05$) such that lower ability adults showed higher word skipping rates. Literacy level was also a reliable independent predictor of skipping ($b = .32$, $SE = .10$, $z = 3.06$, $p < .01$), such that more skilled readers showed higher rates of word skipping. Finally, for probability of refixation, literacy level was the only significant predictor ($b = -.42$, $SE = .06$, $z = -6.79$, $p < .001$), such that more skilled readers showed a lower probability of refixating. No other individual difference measures significantly predicted saccadic eye-movement behaviour.

Distributional analyses

First-fixation duration distribution. The top three panels of Figure 1 present the best-fit regression lines for the effects of literacy on each ex-Gaussian parameter, and Table 4

presents parameter estimates and standard errors from the regression model. Notably, the μ parameter showed no reliable influences of any individual difference variable, indicating that individual differences did not modulate the overall central tendency of first-fixation duration distributions. In contrast, both age and literacy skill were significant predictors of σ , such that fixation-time variability was larger among readers who were older (see also Payne & Stine-Morrow, 2014) and among readers who had lower

literacy skill. τ , which indexes the proportion of extreme fixation durations, was uniquely related to reading level, such that lower literate adults were more likely to show a larger proportion of very slow fixation durations throughout the sentence.

Although the effects of literacy skill were analysed as a continuous variable, Figure 2a plots the probability density function of the estimated ex-Gaussian parameters for first-fixation duration separately for higher literate adults (above the median reading grade level of 9.5) and lower literate adults (below the median reading grade level of 9.5) as a way of visualising literacy differences across the first fixation and gaze distributions. Density functions were estimated via Monte Carlo simulation ($n = 10,000$) from the model estimated ex-Gaussian parameters, where each distribution was generated by summing a sample from a normal distribution with mean μ and standard deviation σ and a sample from an exponential distribution with the rate parameter $1/\tau$. Effects on μ appeared similar for high-literate and low-literate adults, indicating that there was not an increase in overall slowing in fixation duration with lower literacy. Instead the two literacy groups differed in the *spread* and *tail* of the RT distribution, such that readers with lower literacy showed more variability and an increased proportion of extremely slow first-fixation durations.

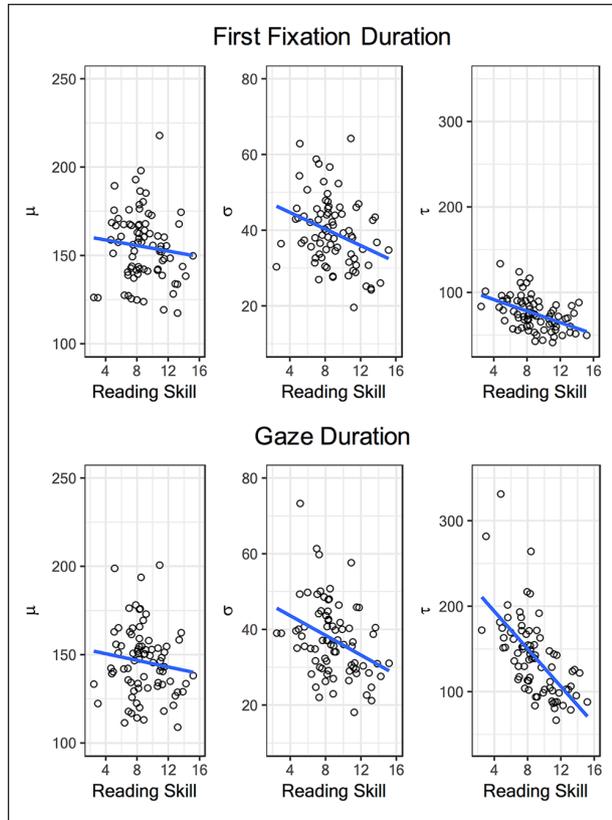


Figure 1. Individual differences in literacy skill and ex-Gaussian parameters for first-fixation duration (top) and gaze duration (bottom). Readers with lower literacy skill show relatively greater fixation-duration variability and an increased proportion of extremely slow fixation durations during reading.

Gaze duration distribution. The bottom three panels of Figure 1 present the best-fit regression lines for the effects of literacy on each ex-Gaussian parameter for gaze duration, and Table 5 presents parameter estimates and standard errors for the regression model. Figure 2b plots the probability density function of the estimated ex-Gaussian parameters for gaze duration separately for those above and below median reading level. Findings for gaze duration were nearly identical to first-fixation duration. There were no reliable predictors of the μ parameter. Both older age and lower literacy skill were associated with greater variability in fixation durations during reading. Finally, literacy was a unique predictor of τ , with lower literate adults showing a greater proportion of extreme fixation durations during reading.

Table 4. Parameter estimates, standard errors, and t tests for regression models of ex-Gaussian parameters for first-fixation duration.

μ	Σ		τ			
	Parameter	b [SE]	t	b [SE]	t	
Literacy	-.05 [.05]	-.91	-.12 [.05]	-2.37	-.17 [.05]	-3.58
Speed	.03 [.18]	.17	.06 [.17]	.37	-.15 [.16]	-.93
Gc	.11 [.16]	.72	.09 [.15]	.63	.06 [.15]	.41
Gf	-.07 [.17]	-.41	-.13 [.16]	-.84	.07 [.15]	.45
Age	.01 [.01]	1.19	.02 [.01]	2.29	-.003 [.01]	-.37

Gc: crystallised intelligence; Gf: fluid intelligence.
Bold values are statistically significant at $p < .05$.

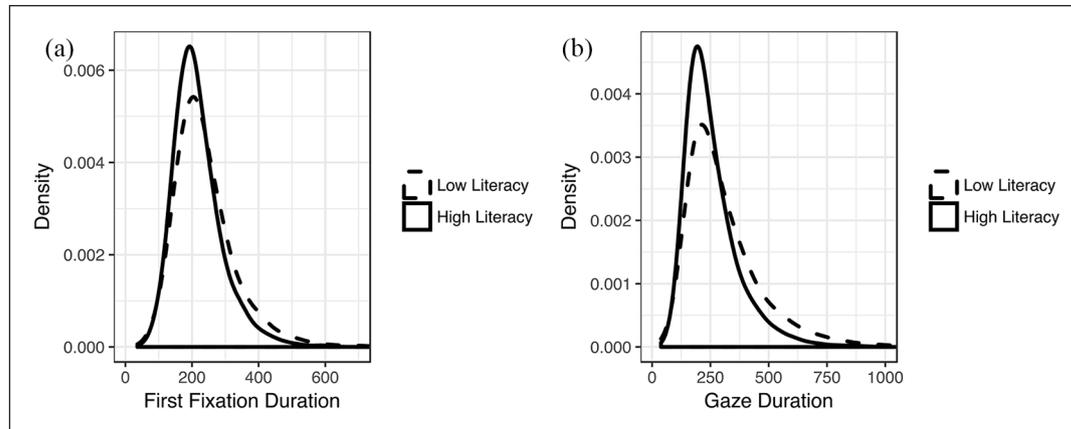


Figure 2. Literacy differences in eye-fixation distributions. Monte-Carlo simulated density functions from best fitting ex-Gaussian parameters for adults with higher-literacy and lower literacy skill for first-fixation duration (a) and gaze duration (b).

Table 5. Parameter estimates, standard errors, and *t* tests for regression models of ex-Gaussian parameters for gaze duration.

Parameter	μ		Σ		τ	
	<i>b</i> [SE]	<i>t</i>	<i>b</i> [SE]	<i>t</i>	<i>b</i> [SE]	<i>t</i>
Literacy	-1.18 [1.08]	-1.10	-1.31 [.49]	-2.65	-10.59 [2.01]	-5.25
Speed	1.23 [3.58]	.34	.59 [1.65]	.36	-10.07 [6.72]	-1.50
Gc	1.96 [3.10]	.63	.49 [1.43]	.34	2.23 [5.83]	.38
Gf	-1.26 [3.27]	-.39	-.84 [1.50]	-.56	3.11 [6.13]	.51
Age	.23 [.17]	1.32	.20 [.08]	2.57	-.13 [.32]	-.42

Gc: crystallised intelligence; Gf: fluid intelligence.
 Bold values are statistically significant at $p < .05$.

Lexical influences on gaze distributions

Figure 3 presents the results from the RM quantile regression analysis. To examine literacy-group differences in each lexical feature across the entire gaze duration distribution, the quantile estimates were aggregated separately for those above and below median reading level and quantile-wise *t* tests were estimated comparing the higher and lower literate adults. Figure 3a presents standardised regression estimates of the effect of each lexical variable at each decile of gaze duration separately for lower literate and higher literate adults. Figure 3b presents the corresponding *t*-values for each estimate in Figure 3a and c presents the *t*-values for the literacy group differences at each decile. As can be seen, differential effects of lexical features were observed across the gaze duration distribution between adults with lower and higher literacy skill.

Word frequency effects (shorter gaze durations to higher frequency words) were robust in nearly every decile, and largely increased in magnitude across deciles, indicating larger effects of word frequency in the tail of the gaze duration distribution, consistent with prior work in literate college-aged adults (Staub et al., 2010). Importantly, this general pattern was observed for both lower literate and higher

literate readers, with both groups showing highly overlapping estimates of word frequency effects across all quantiles and no evidence for systematic literacy differences. In contrast, word length effects manifested a clear difference between lower and higher literate adults. Both lower and higher literate adults fixated on longer words for more time, with effects that appeared largely invariant across the distribution. However, lower literate adults showed a greater sensitivity to word length, such that they showed differentially longer gaze durations on longer words than higher literate adults.

Different from effects of length and frequency, effects of phonological and orthographic neighbourhood were not seen across the full distribution of gaze durations. Nevertheless, a consistent pattern occurred, with effects of both phonological and orthographic neighbourhood selectively in the higher deciles of the distribution and in higher literate adults. For higher literate adults, words with larger phonological neighbourhoods (i.e., lower PLD20 scores) had shorter gaze durations, an effect that was only reliable at the tail of the distribution. For lower literate adults, this effect was in the opposite direction, suggesting greater interference from words with greater neighbourhoods. Significant literacy effects emerged at the deciles 6 and 8 through 10. The effects of orthographic neighbourhood

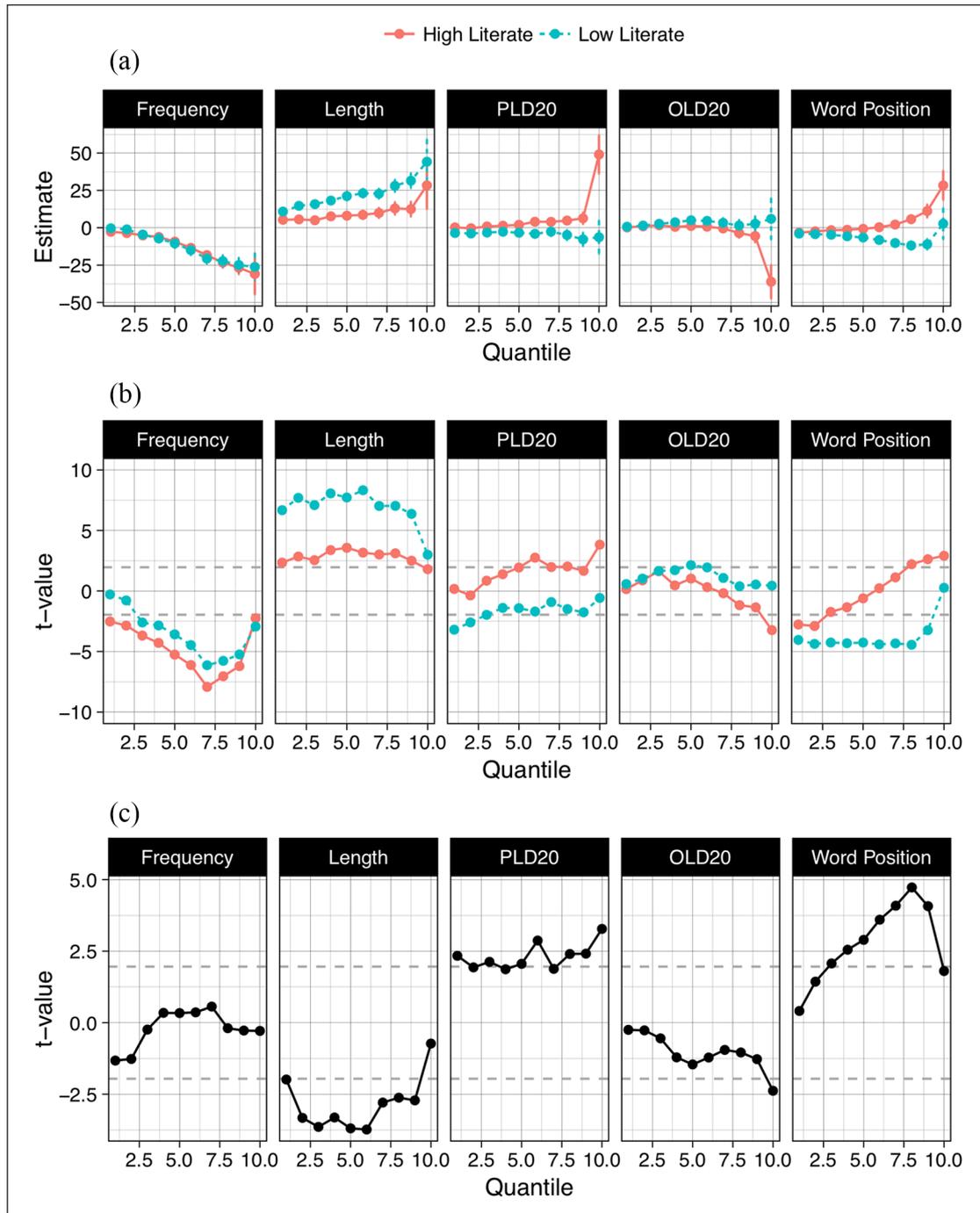


Figure 3. Results from repeated-measures multiple quantile regression analysis of lexical features on gaze duration for lower literate and higher literate readers. Figure 3a presents standardised regression estimates of the effect of each lexical variable at each decile of gaze duration separately for lower literate and higher literate adults (see text for details). Figure 3b presents the corresponding *t*-values for each estimate in Figure 3a separately for both lower and higher literate adults, and Figure 3c presents the *t*-statistics for the literacy group differences at each decile. In Figure 3b and c, the grey dotted horizontal lines indicate upper and lower thresholds for statistical significance.

patterned in the opposite direction. For higher literate adults, words with many orthographic neighbours (i.e., lower OLD20 scores) showed longer gaze durations for the slowest gaze durations (i.e., only in the 10th decile), suggesting that, in contrast to phonological neighbours,

orthographic neighbours produced interference with processing—but only among proficient readers. Significant literacy differences emerged selectively in this slowest quantile of gaze durations, such that only higher literate adults showed a sensitivity to orthographic neighbour-

hood. Processing among lower literate adults was not significantly affected by the orthographic neighbourhood.

These opposing effects of orthographic and phonological neighbourhood among more highly literate adults are interesting and unexpected. Given the high-item correlation between PLD20 and OLD20, we conducted a sensitivity analysis to determine how PLD20 and OLD20 effects vary when each effect is estimated without controlling for the other. We re-fit two reduced versions of the RM quantile regression model, one without OLD20 and one without PLD20, to estimate the zero-order effects of these variables on the gaze duration distribution to further understand this pattern of results. In the reduced model removing OLD20, the effect of PLD20 among higher literate adults was robust and remained significant in the 10th decile. However, in the model removing PLD20, the effect of OLD20 among highly literate adults was reduced to non-significance. This pattern of findings suggests that PLD20 may be acting as an inconsistent mediator—or suppressor—of the effect of OLD20 in higher literate adults (see MacKinnon et al., 2000). The implications of this finding are discussed in more detail in the discussion below.

Finally, word position had a reliably larger effect on gaze durations for lower literate readers compared with higher literate readers. For readers with lower literacy skill, the effect of word position was consistently facilitative, such that readers fixated on words in later positions for less time. This effect, however, was reduced for words in the tail of the gaze distribution. In contrast, higher literate readers did not show a robust word position effect.

Discussion

The primary goal of this study was to characterise the effects of literacy skill on eye-movement control during reading in a community-dwelling sample of adult readers. This investigation was motivated by two factors. First, there is a growing interest in characterising individual variation in the basic factors underlying real-time language comprehension outside of typical college-aged samples, whose processing is not likely to be characteristic of reading across the adult population (Schroeder et al., 2015). Second, there remains a dearth of process-based research in the adult literacy skill development literature, and that lack is an impediment to the development of approaches for improving literacy among adults. Below, we discuss implications of our findings for the understanding of adult literacy and real-time sentence comprehension.

Literacy differences in global eye-movement behaviour

A number of key findings emerged in the global analyses of literacy differences in eye-movement control. Overall lower literate readers showed longer average first-pass

reading times (first-fixation duration and gaze duration) as well as longer total reading times and slower reading rates, replicating prior work (Ashby et al., 2005; Brysbaert, 2019; Chace et al., 2005; Kuperman & Van Dyke, 2011). Beyond effects on average fixation durations, we focused specifically on the underlying fixation duration distributions to quantify individual differences in intra-individual variability in eye-movement control during reading. Indeed, this study is, to our knowledge, the first to characterise individual differences in fixation duration distributions as a function of literacy skill. Staub and Benatar (2013) showed that parameters of fixation duration distributions during sentence reading are stable and reliable trait-like features of individual readers. Other related work has shown that individual differences in ex-Gaussian distribution parameters during self-paced reading are uniquely sensitive to individual difference factors, such as age and working memory (Payne & Stine-Morrow, 2014). The current study extends this prior work by showing that distributional features of eye-fixation durations during reading are related to individual differences in literacy skill.

For both first-fixation durations and gaze durations, analyses revealed that literacy effects on the ex-Gaussian μ component, indexing the central tendency of fixation duration, were negligible. The current study, as well as in prior work focusing on average fixation times (e.g., Ashby et al., 2005; Blythe & Joseph, 2011; Chace et al., 2005), found that lower literacy is associated with slowing of reading rate and longer fixation durations on average. Our distributional results suggest that these average differences are not driven by a shift in the fixation duration distribution (the μ parameter); that is, first-pass word fixation times do not appear uniformly slower across all words among lower literate readers. Instead, literacy level appears to more strongly predict changes in the *shape* of the fixation duration distribution, with lower literate adults showing increased intra-individual variability in first-pass fixation durations. Lower literate readers showed notable increases in the modal variance (σ) and the proportion of extremely long fixation durations (τ), resulting in a differentially broader and more skewed fixation time distribution. Thus, overall fixation durations, which have been taken to reflect early stages of lexical processing, do not appear to be generally slowed among lower literate adults (i.e., all fixations are not slower). Instead, reading patterns in lower literate adults are more variable and more subject to extremely long first-pass durations on a subset of words. Below, we outline a number of potential mechanisms for these distributional changes in eye-movement control in adults with lower literacy skill.

Staub and Benatar (2013) distinguished between factors that impact word processing difficulty and factors that impact the rate of word processing disruptions (see also Reingold et al., 2012). They argued that factors related to processing ability (e.g., slowed perceptual or linguistic

processes during reading) are likely to result in uniform shifts of the fixation duration distribution across all words, exerting a large influence on μ . This is consistent with the idea that such perceptual and lexical processing factors have a direct influence on eye-movement control and, as such, should influence processing difficulty on nearly all trials. Under an account of slowed lexical processing among low-literate adults (e.g., Blythe & Joseph, 2011; Rayner, 2003), we would expect that such increases in processing difficulty would shift the entire reading time distribution for lower literate adults, resulting in generalised slowing of reading rate.

Staub and Benatar (2013) claimed that effects on τ , in contrast to those on μ , are likely to reflect cases in which normal perceptual or lexical processing does not succeed, and thus, some additional repair or recovery process must occur on a subset of trials, leading to a skewed distribution. For example, they argued that readers may initially fail to recognise very low frequency words or may fail to integrate word meanings into the message-level representation of the sentence. Such cases are likely to result in uncharacteristically long fixation durations, resulting in fixation duration distributions with an increased skew. Under this account, our findings would suggest that lower literate adults experience an increased likelihood of disruption of normal lexical processing. Such findings are compatible with theories predicting underdeveloped lexical representations among less literate adults, such as the lexical quality hypothesis (Perfetti, 2003), in which lower literate adults would have an increased likelihood of encountering words that present challenges to normal lexical processing, resulting in increased rates of disruption and increased variability in word reading times.

An alternative, but not mutually exclusive, account is that increased τ effects in reading may partially reflect episodes where attentional control is differentially recruited to succeed in normal reading (Luke & Henderson, 2013; McVay & Kane, 2012; Payne & Federmeier, 2017; Payne & Stine-Morrow, 2012). Indeed, outside of the reading literature, increases in the τ parameter have been argued to index domain-general cognitive processes related to inhibitory control, competition, conflict resolution, and other aspects of demanding post-perceptual and decision-related processing. Such experiments have produced highly consistent results that increases in τ occur among task conditions that are the most attentionally demanding (Balota & Spieler, 1999; McVay & Kane, 2012; Schmiedek et al., 2007).

Related to this, WM capacity has been shown to correlate strongly with τ in tasks that place high demands on sustained attention control (Schmiedek et al., 2007; Tse et al., 2010). Such WM-dependent effects have also been observed on τ during self-paced word reading in younger and older adults (Payne & Stine-Morrow, 2014). Finally, recent findings from Payne and Federmeier (2017), using

a novel method of co-registering word-by-word reading times with event-related brain potentials (ERPs), showed that trials exhibiting increased distributional skewing (τ effects) during reading are associated with an increased anterior N2, an electrophysiological component generated by the anterior cingulate cortex that has been strongly linked to domain-general conflict resolution and the immediate cognitive control of action (e.g., cancelling a pre-potent motor response during conflict resolution; Folstein & Van Petten, 2008). Under this hypothesis, trials in the tail of the distribution of motor output measures (e.g., RTs, fixation times) may be those for which attentional demands are the greatest. Such findings would also be consistent with some models of eye-movement control that posit that words with the longest fixations are disproportionately impacted by higher order cognitive processes, whereas faster fixation durations are more directly determined by oculomotor programmes (Yang & McConkie, 2001). Under this account, among lower literate adults, the act of reading is disproportionately attentionally demanding. Importantly, we did not observe that any of the domain-general measures of cognitive functioning (psychomotor speed, fluid and crystallized ability) were predictive of τ effects. Thus, whatever the precise mechanism, the observed skewing of the fixation distribution in this case seems to be specifically linked to reading ability.

A third possibility that may explain individual differences in these distributional findings is that lower literate adults show generalised deficits in eye-movement control during reading, in part because the motor programme is less well-practised among poor readers who are, of course, less likely to read. In such cases, one may expect lower literate adults to show differences in eye-movement control in other pseudo-reading type tasks (e.g., reading strings of the letter 'Z'; Luke & Henderson, 2016; Rayner & Fischer, 1996). Luke and Henderson (2016) used such a method to examine differences in eye-fixation distributions when reading meaningful and non-meaningful stimuli among skilled adult readers. Interestingly, only fixation durations in the tail of the distribution were affected by content meaningfulness (reading Z's versus reading real sentences). Similar experimental paradigms could be adopted in future research comparing differences in eye-movement distributions among literate and non-literate readers when reading meaningful and non-meaningful content to address such questions about oculomotor differences.

Thus, although the exact mechanism(s) generating the observed increases in intra-individual variability in fixation durations during reading among lower literate adults remain unclear, the finding that literacy is not linked to shifts in the fixation duration distribution, but instead is associated with more variable and extreme fixation durations, is critical to our understanding of the source of adult literacy issues in real-time reading processes. This may hold keys for the design of future interventions aimed at

improving adult literacy skills. For example, interventions designed around the idea of increasing overall reading rate (e.g.,) may overlook the dynamics of volitional control during reading (Payne & Federmeier, 2017; Schotter & Payne, 2019). Indeed, programmes on effective speed reading (i.e., maintaining high comprehension levels with rapid text reading) have been called into question (Rayner et al., 2016; Schotter et al., 2014) for exactly this reason. Effective comprehension requires the real-time regulation of attention to repair and revision processes that vary on a word-by-word basis and require more time to process.

We also found that lower literate adults showed increased rates of regressive eye movements and first-pass refixations and decreased word skipping rates, consistent with prior work (e.g., Reichle et al., 2013). Regressive saccades during sentence reading have been argued to reflect periods of disruption in ongoing sentence processing (Rayner et al., 2009). Collectively, our findings suggest that lower literate readers struggled to fluently move through the sentence, perhaps in part because of an increased rate of disruption in early stages of word recognition, as indexed by the increased τ effects on first fixations and gaze durations. We also observed that lower literate adults in our sample show increased rates of refixation. Similar findings have been observed in developing readers, where children tend to refixate words more frequently (Blythe & Joseph, 2011). These refixations may partially explain the larger literacy-driven differences in gaze duration observed in the current study. That is, lower literate adults may show more skewing in part due to increases in the likelihood of refixating. However, because similar distributional results were observed in first-fixation durations, refixations cannot completely account for distributional differences. Rather, the increases in distributional skewing and refixation rate may be driven by a common cause—slowed lexical processing. In fact, Reichle and colleagues (2013) presented simulations in the E-Z Reader model showing that increased refixation rates among lower literate readers could be explained by slowed lexical processing.

For word skipping behaviour, an interesting pattern emerged with higher rates of word skipping not only among adults with higher literacy skill but also among adults with lower fluid intelligence. These independent and divergent influences suggest that overall word skipping rates may be multiply determined. For instance, the increased skipping rates among highly literate adults may reflect a higher fidelity of parafoveal word processing (e.g., Chace et al., 2005), allowing higher literate adults to partially identify more words in parafoveal vision, resulting in subsequent skipping. However, the finding that increased skipping is also observed among lower ability adults is less clear.

One possibility is that lower ability adults are adopting a more “risky reading” strategy (McGowan & Reichle, 2018; Rayner et al., 2003), wherein they are more likely to “guess” the identify of upcoming words as a way of

compensating for either slowed lexical processing or reduced parafoveal processing. However, the canonical risky reading pattern is associated with increases in regressive eye-movement behaviour that occurs when guesses are incorrect and require revision. Such a pattern was not observed among lower fluid ability adults in the current study. It is possible that adults with lower fluid ability do not engage in this revision process, instead adopting an underspecified “good-enough” approach (Ferreira et al., 2002) to comprehension. Overall, these divergent effects of individual differences in word skipping suggest that broad statements about word skipping reflecting a specific cognitive operation (e.g., disfluency) may not be entirely accurate, as such effects seem to be simultaneously related to both increased reading skill and lower cognitive ability.

Lexical effects on gaze distributions

Towards our second goal of examining literacy effects on sensitivity to lexical features during reading, we reported an exploratory analysis focusing on the effects of multiple lexical features (word length, frequency, density of orthographic and phonological networks, and word position) on gaze duration distributions among lower and higher literate adults. We used a novel application of RM quantile regression (e.g., Risse & Kliegl, 2014) in an exploratory corpus-based analysis (e.g., Angele et al., 2015; Kuperman et al., 2010), to simultaneously examine the impact of these multiple lexical features on word processing during normal reading. The use of quantile regression allowed us to infer how sensitivity to these lexical features varied across the entire gaze distribution.

The most notable finding was that all lexical effects tended towards larger relative effect sizes as overall gaze durations increased (see Figure 3), suggesting that lexical features are stronger determinants of eye-movement control among longer gaze durations in the tail of the distribution, compared with shorter gaze durations. Such findings are generally in line with theories and models of eye-movement control that propose that longer fixations are under greater influence of cognitive control compared with shorter fixations (e.g., Engbert et al., 2005; Henderson & Luke, 2012; Nuthmann & Henderson, 2012; Yang & McConkie, 2001).

Concerning specific lexical influences, first, we observed that effects of word frequency increased across the gaze duration distribution, indicating a differential frequency effect in the tail of the distribution. These findings are consistent with a number of findings showing that lower frequency words show pronounced rightward RT skewing across tasks (e.g., lexical decision, eye movements in reading) and measures (e.g., Reingold et al., 2012; Staub et al., 2010; Yap & Balota, 2007). Interestingly, there was no difference in frequency effects

between lower and higher literate adults across the gaze duration distribution, despite the clear global increase in skewing in lower literate adults, suggesting that literacy level does not appear to substantially modulate the lexical-semantic processes indexed by word frequency effects. The lack of literacy differences in the effects of word frequency may suggest that lexical processing disruption is not the primary driver behind the observed global increase in intra-individual variability among lower literate adults. That is, the lack of a literacy difference in lexical processing is inconsistent with accounts positing that lower literate readers show increased skewing because they are experiencing greater rates of lexical disruption for low frequency and unfamiliar words (see Staub & Benatar, 2013).

Although word length effects were more pronounced in lower literate compared with higher literate readers, these effects were largely uniform across the gaze duration distribution. This finding is consistent with prior work showing that children who are learning to read and adults with dyslexia show larger word length effects (Hawelka et al., 2010; Rau et al., 2014; Tiffin-Richards & Schroeder, 2015). Such findings have been interpreted as reflecting less efficient lexical processing among lower literate readers, consistent with the lexical quality hypothesis (Perfetti, 2007). For example, in applying dual-route models of single-word reading to eye-movement data (Hawelka et al., 2010; Rau et al., 2014), some have argued that increased length effects among less skilled readers may reflect a less efficient automatic lexicalized whole-word recognition route. As such, less skilled readers are more reliant on a second serial sub-lexical processing route. Under this account, the lower literate adult readers in the current study, who have lower quality lexical representations, must rely more on serial sub-lexical processing that increases with the number of additional graphemes that need to be encoded. This, combined with the reduced perceptual span for encoding written words (Veldre & Andrews, 2015), may lead to uniformly larger word length effects on gaze durations among lower literate readers.

In contrast to the direct effects of length and frequency of the word itself, which were robust across the entire gaze distribution, effects of a word's phonological and orthographic neighbourhood appeared to be strongly dependent on literacy level, and were restricted to the longest gaze durations only. Effects of both ON and PN among proficient readers were most strongly observed in the slowest decile of the distribution. Among these trials and readers, gaze durations were shorter to words with higher PN (lower PLD 20 scores) and with lower ON (higher OLD 20 scores). Thus, effects of phonological and orthographic neighbourhood appeared to dissociate, such that having many neighbours with similar phonology facilitated word processing, but having many orthographic neighbours interfered with word processing. That such effects occurred

only among words with the longest gaze durations suggests that the transient activation of orthographically and phonologically similar representations during reading may not have obligatory and uniform effects on gaze patterns in natural reading, only influencing a subset of words.

Similar results have been reported in auditory word recognition (Roux & Bonin, 2013; Ziegler et al., 2003; Ziegler & Muneaux, 2007). For example, Ziegler and colleagues (2003) showed evidence for *inhibition* of auditory lexical decision times when words had many phonological neighbour, but *facilitation* when words had many orthographic neighbours. Ziegler and Muneaux (2007) showed that these effects were dependent upon reading skill level. Skilled child readers, but not beginning or dyslexic readers, showed both competing phonological and orthographic activation on auditory word naming times. In the current study, we observed a similar (but inverted) pattern, whereby words with high PN facilitated processing but words with high ON inhibited processing. Indeed, this inverted pattern during reading, as opposed to listening, is directly predicted by interactive-activation (IA) connectionist models of word recognition (Ferrand & Grainger, 1994; McClelland & Rumelhart, 1981). In the bimodal IA model, for example (Ferrand & Grainger, 1994), lateral inhibitory connections are assumed within a representational level (i.e., within orthography or phonology), whereas excitatory connections are assumed between representational levels (i.e., between orthography and phonology). Thus, when a word is read (instead of heard), the within-representation orthographic connections inhibit processing, slowing reading time for words with high ON density. In contrast, the between-representation phonological connections facilitate word processing, leading to faster word reading times for words with high PN density. Critically though, these effects were also literacy dependent (see also Ziegler and Muneaux, 2007). Without proficient reading skill, phonological and orthographic neighbours did not show excitatory or inhibitory effects on gaze duration.

In our sensitivity analyses, where we examined effects of PN and ON without controlling for the other, we also observed that the PN effects were robust to control of ON (i.e., the excitatory effects were present regardless of orthographic *N*). However, the inhibitory ON effects were only present when controlling for PN. This pattern of findings, where the ON effect increased after accounting for PN, suggests that PN is acting as a suppressor (or inconsistent mediator, see MacKinnon et al., 2000) of the ON effect. The inhibitory effect of ON is revealed only when PN is accounted for because of their strong positive association with each other but opposing effects on gaze durations, washing out the total effect. This finding is generally consistent with the idea that ON and PN effects act in opposition to jointly predict word reading time, despite their high positive correlation. Importantly, we observed that greater literacy skill was predictive of both

phonological and orthographic neighbourhood effects during reading, supporting claims that orthographic and phonological similarity are important dimensions in models of visual word recognition and the development of fluent reading (Grainger, 2018). This study is the first to our knowledge to show literacy-dependent bimodal activation of orthographic and phonological neighbours in silent reading in the absence of explicit task demands. However, it is important to note that these findings should be interpreted with some caution as this analysis was exploratory in nature.

Finally, we observed differences in the effect of word position on gaze distributions as a function of literacy skill. Here, lower literate adults showed greater sensitivity to word position across most of the gaze distribution compared with higher literate readers. Among lower literate readers, increasing word position was associated with facilitated gaze durations. To the extent that increasing ordinal position is correlated with accumulating message-level semantics during reading (Dambacher et al., 2006; Payne et al., 2015, 2018; Payne & Federmeier, 2019; Stine-Morrow et al., 1996, 2008; Van Petten & Kutas, 1990), these findings would be broadly consistent with the long-standing idea that poor readers show greater contextual facilitation (e.g., Ashby et al., 2005). Interestingly, this facilitative effect was more apparent in the fastest trials among lower literate adults, whereas slower trials elicited more positive word position effects among higher literate adults. These findings suggest that lower and higher literate adults may be responsive to different aspects of ordinal word position. Kuperman and colleagues (2010) suggest that word position effects on eye movements may be multiply determined, with beginning of sentence facilitation effects (e.g., “start-up” effects) driven by a strategic oculomotor programme of saccade planning, but later effects reflecting slowing associated with end of sentence comprehension and semantic integration processes (e.g., “wrap-up effects” see Payne & Stine-Morrow, 2014; Stine-Morrow & Payne, 2016). Taken together with the previously discussed theories of distributional differences in the cognitive control of fixations (e.g., Yang & McConkie, 2001), under this account, effects of word position may dissociate across the fixation distribution and literacy group because lower literate adults may be more sensitive to early visuo-motor mediated “start-up” effects, whereas more skilled readers show differential slowing selectively in the tail of the distribution, reflecting end of sentence comprehension-related processes. Indeed, prior work in literate adults has shown that both end-of-sentence wrap-up effects (Payne & Stine-Morrow, 2014) and violations of predictability at the ends of sentences (Payne & Federmeier, 2017) selectively influence trials in the tail of the reading time distribution. Although this account is speculative at this point, the findings suggest that word position effects influence the

distribution of fixations among lower and higher literate readers in contrasting ways.

Limitations and future directions

Important limitations and avenues for future work need to be addressed. Notably, we adopted a correlational corpus-based approach to examine intra-individual variation in sentence reading as a function of reading skill. Although corpus-based approaches have been widely used in the eye-movement and reading literature and have provided invaluable insights into the cognitive mechanisms of eye-movement control in reading (e.g., Kliegl et al., 2004; Kuperman et al., 2010; Kuperman & Van Dyke, 2011; Luke et al., 2018), such findings are nevertheless correlational, and potentially subject to multiple sources of confounds (see Angele et al., 2016, for a recent discussion). Importantly, despite our best efforts in our exploratory lexical analyses to simultaneously account for many lexical covariates statistically, we cannot rule out that some reported effects were not partially influenced by other lexical features that were not accounted for. Therefore, in future research, experimental replication of some of the most interesting findings reported here, including the uniform literacy differences in word length, and the stronger ON and PN effects on τ among highly literate adults, is necessary. Nevertheless, the current findings are valuable in highlighting clear differences in global eye-movement behaviour among adults varying in literacy skill in a large and diverse sample that was well powered to detect individual differences in fixation distributions.

Conclusion

Characterising individual differences in eye-movement control during reading offers a number of potential advances into understanding real-time comprehension processes in populations with heterogeneous reading comprehension difficulties, such as adult literacy learners. Monitoring eye-movement control during reading has the potential to offer a more detailed characterization of the real-time sources of comprehension difficulties, without imposing additional task demands or responses. We view this as a potential major strength of the use of eye tracking for furthering our understanding of reading comprehension difficulties and individual differences in reading skill. In fact, subtle assessment differences can lead to differences in reading performance that are not truly related to reading skill. For example, the commonly used Nelson–Denny reading comprehension test is used to assess reading skill level in clinical, cognitive, and educational assessments. One subtest of the Nelson–Denny requires reading passages and answering multiple choice questions. Ready and colleagues (2013) showed that question accuracy on the Nelson–Denny reading subtest is correlated with fluid intelligence even when

participants are administered the test without the associated passages to read (and, thus, may have little to do with actual reading comprehension ability).

However, before eye tracking can eventually develop as a useful diagnostic tool for real-world reading comprehension difficulties, substantial work remains to be done to understand the mechanisms of literacy skill development in adulthood and to align models of reading from cognitive psychology and cognitive neuroscience with evidence-based research from adult literacy learning and remediation. As a first step towards these goals, we adopted a fine-grained analysis of fixation duration distributions to examine whether such measures can characterise difficulties in language processing and literacy skill in a diverse community-based sample of adults. These findings clearly showed that individual differences in literacy skill are associated with substantial differences in eye-movement variability and control during reading, revealing the dynamic nature of real-time comprehension processes.

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Supplementary Material

The supplementary material is available at qjep.sagepub.com

Note

1. Fitting a model with random slopes across items for each individual difference measures failed to converge, unless covariances between all random slopes and intercepts were set to 0 (Barr et al., 2013). No random slopes were significantly different from zero for either regressions or word skipping. Likelihood ratio tests were conducted for both skipping and regressions comparing the full random-effects model with a simplified random-intercepts only model. In neither case did the more complex model result in a significant improvement in fit. Thus, the more parsimonious random intercept models (Bates et al., 2015) are presented.

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