Spelling ability selectively predicts the magnitude of disruption in unspaced text reading

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Abstract

We examined the effect of individual differences in written language proficiency on unspaced text reading in a large sample of skilled adult readers who were assessed on reading comprehension and spelling ability. Participants' eye movements were recorded as they read sentences containing a low or high frequency target word, presented with standard interword spacing, or in one of three unsegmented text conditions that either preserved or eliminated word boundary information. The average data replicated previous studies: unspaced text reading was associated with increased fixation durations, a higher number of fixations, more regressions, reduced saccade length, and an inflation of the word frequency effect. The individual differences results provided insight into the mechanisms contributing to these effects. Higher reading ability was associated with greater overall reading speed and fluency in all conditions. In contrast, spelling ability selectively modulated the effect of interword spacing with poorer spelling ability predicting greater difficulty across the majority of sentence- and word-level measures. These results suggest that high quality lexical representations allowed better spellers to extract lexical units from unfamiliar text forms, inoculating them against the disruptive effects of being deprived of spacing information.

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Statement of Public Significance

The spaces between words serve an important function in many written languages. Spaces help guide readers' eye movements across a line of text and aid reading by providing a cue to the word boundaries. However, unspaced text is prevalent in some settings (e.g., Internet domain names, email addresses, hashtags) and some languages are written without interword spaces (e.g., Chinese, Japanese). Reading is substantially more difficult when the spaces are removed from English text but it is unclear whether good and poor readers experience similar difficulty. We investigated whether the use of spaces and word boundary cues depends on reading skill by recording the eye movements of university students as they read spaced and unspaced text. The participants were assessed on their vocabulary, reading comprehension, and spelling ability. We found that good and poor readers showed similar disruption from unspaced text. However, poor spellers were much slower at reading unspaced text than good spellers. These results suggest that high spelling ability aids the reading of text in unfamiliar formats. Precise knowledge about the identity and order of letters in words is critically important for proficient reading.

Reading involves much more than identifying words. Fluent comprehension requires rapid decisions about when and where to move the eyes to optimize co-ordination of the perceptual, cognitive, and oculomotor processes required to extract lexical information from text and integrate it with the readers' semantic, syntactic, and world knowledge to construct meaning. Unlike word identification, which is a highly practised skill that requires explicit instruction, the complex oculomotor processes required for reading text are acquired implicitly with little, if any, formal instruction. Although readers converge on what appears to be an optimal eye movement strategy that aligns with the temporal and spatial constraints of the oculomotor system (Rayner, 2009), there are systematic individual differences among adult readers in eye movements as a function of written language proficiency in both first language (e.g., Kuperman & Van Dyke, 2011; Taylor & Perfetti, 2016) and second language reading (Cop, Drieghe, & Duyck, 2015).

Radach and Kennedy (2004, 2013) have highlighted the need for systematic research on individual differences to advance theories and models of eye movement control in fluent reading. The present study is part of a research program designed to address this goal by examining variability in skilled readers' eye movements as a function of individual differences in reading and spelling ability. Our inclusion of measures of spelling ability as well as reading comprehension is motivated by the influential *lexical quality hypothesis* of reading skill (Perfetti, 1992, 2007). According to this view, reading skill is a function of the quality of a reader's lexical representations. Lexical quality encompasses the precision, coherence, and redundancy of the orthographic, phonological, and morpho-semantic knowledge about a word in memory. Within this framework, spelling ability is argued to provide a more robust index of lexical precision than passage comprehension, the most typical measure of reading ability (Andrews, 2012, 2015; Perfetti, 1992). Consistent with this view, spelling ability has been found to selectively predict eye movement indices of word identification and oculomotor control in normally spaced text (Veldre & Andrews, 2014, 2015a, 2015b, 2016a, 2016b).

To gain further understanding of the basis of these differences, the present study investigated how written language proficiency affects the use of spaces and word boundary cues in reading. Specifically, we sought to establish whether reading and spelling ability predict the magnitude of disruption from removing interword spaces in reading. If lexical precision is critical to effective co-ordination of the component processes in reading, effects of spelling ability should be magnified in unsegmented text that distorts the cues which normally support the automatic skill of eye movement control.

The Role of Spaces in Reading

In English, like most alphabetic languages, interword spaces provide an unambiguous cue to word boundaries. Spaces also provide low spatial frequency information about the length and physical extent of the fixated word, as well as upcoming words, that facilitates locating word units in parafoveal and peripheral regions in which visual acuity is low. Evidence from studies using the *moving window paradigm* (McConkie & Rayner, 1975) suggests that readers use this coarse-scale information for oculomotor planning: reading fluency is reduced when information is masked even up to 15 characters to the right of the point of fixation, which is well beyond the extent of parafoveal vision (see Rayner, 2014, for a review).

Investigations of reading spatially transformed text have established the utility of spaces by showing that reading speed is reduced by between 30 and 50% for unsegmented text. Removing or filling interword spaces with random letters,6digits6or☐ shapes☐results in an increased number of fixations, inflated fixation durations, reduced word skipping, more regressive eye movements, and reduced saccade lengths (Epelboim, Booth, Askenazy, Taleghani, & Steinman, 1997; Epelboim, Booth, & Steinman, 1994; Malt & Seamon, 1978;

McGowan, White, Jordan, & Paterson, 2014; Paterson & Jordan, 2010; Perea & Acha, 2009; Perea, Tejero, & Winskel, 2015; Pollatsek & Rayner, 1982; Rayner, Fischer, & Pollatsek, 1998; Sheridan, Rayner, & Reingold, 2013; Sheridan, Reichle, & Reingold, 2016; Spragins, Lefton, & Fisher, 1976; Yang & McConkie, 2001). Spaces may also facilitate the extraction of letter information by reducing visual crowding and lateral masking. This is supported by evidence that small increases in interword spacing are associated with increased reading speed (Drieghe, Brysbaert, & Desmet, 2005; Slattery & Rayner, 2013).

A number of factors potentially contribute to spacing effects. First, a lack of interword spaces disrupts oculomotor planning. Eye guidance in reading English depends on identifying word units, as evidenced by the existence of a *preferred viewing location* (PVL) in saccade landing positions. Initial fixations on words cluster around a predictable location that is approximately half-way between the beginning and the center of the word (Rayner, 1979). When spaces are removed from English text, saccades land significantly closer to the word beginning, implying that readers typically use parafoveal information about word spaces to plan saccades that target the optimal location for lexical processing of upcoming words (Morris, Rayner, & Pollatsek, 1990; Pollatsek & Rayner, 1982; Rayner et al., 1998).

Alternatively, the shorter saccades observed in unspaced text reading may reflect a more cautious reading strategy in response to the increased difficulty of unspaced text, rather than disruption of saccade programming processes. In unspaced text, the optimal viewing position may be closer to the word beginning to facilitate disambiguation of the initial word boundary. Consistent with this possibility, spacing effects on landing position have also been observed in experienced readers of unspaced languages. In both Chinese and Japanese, which are naturally unspaced scripts, saccade landing positions cluster at the word beginning (Kajii, Nazir, & Osaka, 2001; Li, Liu, & Rayner, 2011; Ma, Li, & Pollatsek, 2015; Zang, Liang, Bai, Yan, & Liversedge, 2013) but when spaces were introduced to text in Japanese *hiragana* (syllabary), the PVL shifted toward the word center, as in English (Sainio, Hyönä, Bingushi, & Bertram, 2007).

Another factor contributing to the disruptive effects of removing word spaces is impairments in word recognition demonstrated by inflation of the *word frequency effect*, an empirical diagnostic of lexical processing. Direct evidence that filling word spaces delays the onset of lexical processing was provided by Sheridan et al.'s (2013) *survival analysis* showing that the impact of word frequency on fixation duration emerged between 20 and 40 ms later in unsegmented text than in normally spaced text. Part of the difficulty associated with lexical processing may derive from ambiguities caused by lexical embeddings within and across word boundaries. Weingartner, Juhasz, and Rayner (2012) showed that high frequency embedded words (e.g., *hat* in *hat*ch) disrupted reading of normally spaced text and adding a space between the constituents of a compound word (e.g., *back hand*) has been found to facilitate the identification of the individual lexemes (Inhoff, Radach, & Heller, 2000; Juhasz, Inhoff, & Rayner, 2005). Such effects may be magnified in unspaced text in which word boundaries are ambiguous. Consistent with this proposal, Perea and colleagues have shown that reading unspaced text is substantially less difficult if word boundary cues are preserved by presenting sentences in alternating**bold** (Perea & Acha, 2009) or in alternatingcolor conditions (Perea et al., 2015). These findings imply that a major source of difficulty in reading unspaced text lies in parsing words from the string of letters that constitute the sentence. The evidence summarized above concerning saccade landing positions implies that parsing often occurs in the parafovea, before a word is directly fixated, in spaced alphabetic text.

Readers also use parafoveal information to initiate the *identification* of upcoming words (see Schotter, Angele, & Rayner, 2012, for a review). Sheridan et al. (2016) found that the disruption caused by unspaced text is at least partly attributable to the reduced efficiency of parafoveal processing. Using the gaze-contingent boundary paradigm (Rayner, 1975) to manipulate the parafoveal preview validity of a low or high frequency target word, they showed that text spacing interacted with both preview validity and word frequency. Consistent with these joint contributions to spacing effects, successful simulation of the data with the E-Z Reader model of eye movement control (Reichle, Pollatsek, Fisher, & Rayner, 1998) required changes to both the lexical and parafoveal processing parameters. Furthermore, survival analyses revealed that the onset of parafoveal processing was delayed in unsegmented text relative to normal text. The reduced parafoveal processing in unspaced text is likely compounded by English readers' unfamiliarity with reading text in this format.

Individual Differences and Spacing Effects

The effects of reading unspaced text are not uniform across readers. Epelboim et al. (1994) found substantial inter-individual variability among adult readers in the extent of disruption caused by the removal of word spaces, with some members of their sample showing almost no cost to reading speed. There is also evidence of systematic variability between reading populations. Spragins et al. (1976) found that adults were more disrupted than children when reading filled-space and unspaced text. Elderly readers have also been found to be more disrupted by unspaced text than young adult readers (McGowan et al., 2014; Rayner, Yang, Schuett, & Slattery, 2013). However, no studies have directly examined how reading proficiency contributes to spacing effects.

Investigations of individual differences among young adults reading normally spaced text have established that parafoveal processing is a major source of inter-individual variability. Better readers and spellers have larger perceptual spans than lower proficiency readers (Veldre & Andrews, 2014; see also Choi, Lowder, Ferreira, & Henderson, 2015). Higher spelling ability in combination with high reading ability has also been found to predict larger effects of parafoveal preview validity (Veldre & Andrews, 2015b, 2016a) and deeper processing of lexical/semantic information from the parafovea (Veldre & Andrews, 2015a, 2016b).

These findings suggest that the speed and efficiency of higher proficiency readers' eye movements may reflect a strategy that depends more heavily on the extraction and use of information from the parafovea and periphery. Readers with high quality lexical representations may, therefore, be more reliant on parafoveal cues such as interword spaces in saccadic planning and word identification. If so, higher proficiency reader/spellers will be relatively *more* disrupted by reading text in which the familiar configurations of words and text that are usually used to support automatic lexical retrieval are obscured or distorted. Such evidence would indicate that the unfamiliar format of unspaced text prevents highly skilled readers from effectively deploying the high quality lexical knowledge and automated procedures that underpin their efficient processing of standard text.

Alternatively, high proficiency readers with high quality lexical knowledge may be better at adapting to the demands of reading unspaced text. The high quality representations indexed by superior spelling ability may enable more effective parsing of words from unspaced text and greater resilience to misleading perceptual information, resulting in relatively less disruption to reading.

The present study

The present study compared reading of normally spaced *'Standard'* text to three spatially transformed conditions that have not been directly compared in previous research. In the *'Numbers'* condition, the inter-word spatial distance was maintained by filling spaces with numerals. In the remaining two conditions, interword spaces were removed entirely. In the '*Capitals'* condition, word boundaries were preserved by presenting alternate words in lower and upper case and in the *'Unspaced'* condition cues to word boundaries were completely absent (see Figure 1). In order to assess the impact of the spacing conditions on lexical processing, the sentences contained a critical target word that was either low or high frequency.

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On the basis of past evidence summarized above, it was predicted that readers would show increased reading times and larger frequency effects in unsegmented text relative to spaced text. Retaining cues to word boundaries in the Numbers and Capitals conditions was expected to reduce the difficulty of parsing words and therefore produce less disruption to reading than the Unspaced condition in which there are no such cues. Differences between the Numbers and Capitals conditions will depend on the trade-off between maintaining the spatial distance and visual format of words in the Numbers condition and the more distinctive word boundary cues, but unfamiliar visual format, of the Capitals condition.

Unlike previous studies, the presentation of conditions was blocked in the present study: the Standard condition was always presented first, followed by counterbalanced blocks of the three unsegmented conditions. There were two reasons for this. First, given our focus on individual differences it was important to establish a pure baseline of the impact of reading and spelling ability on reading of normally spaced text to allow clear comparisons with the unspaced conditions. Intermixing of normally spaced and unspaced trials may induce a more cautious reading strategy in some readers, even for standard text, which may depend on, or interact with, reading proficiency. More generally, the ability to adapt to an unfamiliar text format with experience may be a source of inter-individual variability. Malt and Seamon (1978) found that after 10 days training in oral reading of filled-space text, participants became faster and made fewer reading errors. However, practice did not completely eliminate the spacing effect. Perea et al.'s (2015) data suggested that practice may play a role even within a single experimental session because disruption from reading unspaced text reduced from the first to the second half of the experiment as participants became more experienced with the unfamiliar format (but see Yang & McConkie, 2001).

The second justification for blocking the spacing conditions is that intermixing normally spaced text with unspaced trials may prevent readers from converging on an optimal strategy for reading unspaced text and therefore artificially inflate spacing effects. Most previous investigations of spacing manipulations have used intermixed conditions making it difficult to disentangle effects of trial-to-trial variability from the effects of spacing *per se*. Evidence of substantial spacing effects in the present study in which the spacing conditions were blocked would confirm that the disruption caused by unspaced text is not an artifact of trial order and rule out explanations based on trial-to-trial adjustment of processing strategy or individual differences in the capacity to adapt to such variation in format.

METHOD

Participants

The participants were 109 undergraduate students from The University of Sydney (mean age = 18.9 years). All had normal or corrected-to-normal vision and began speaking English before age 6. Participants received partial course credit as compensation.

Measures of Written Language Proficiency

All participants completed several measures of written language proficiency. Vocabulary and passage comprehension were assessed with the Nelson-Denny Reading Test (Brown, Fishco, & Hanna, 1993. Participants also completed a 20-item spelling dictation test and an 88-item spelling recognition test (see Andrews & Hersch, 2010). Average performance on each of these assessments is summarized in Table 1. Based on published four-year US college norms for the Nelson-Denny Reading Test, total scores ranged between the 26th and 98th percentile, with mean performance at the 71st percentile, indicating that the average performance for the sample was high relative to the population of college students.

---INSERT TABLE 1 HERE ---

As summarized in Table 1, scores on the two subsections of the Nelson-Denny test were highly correlated (*r*=.69) so standardized scores on the two tests were averaged to form a composite index referred to as *reading ability*. Similarly, standardized scores on the two highly correlated spelling assessments (*r*=.78) were averaged to provide an index of *spelling ability*. Reading and spelling ability were only moderately correlated (*r*=.46) and were therefore retained as separate predictors in all analyses.

Materials and Design

The stimuli were 120 sentence frames, 80 of which were adapted from Juhasz, Liversedge, White, and Rayner (2006). The sentences were constructed so that they could plausibly contain either member of a pair of critical target words. Each target word pair contained a high frequency noun (*M*=155.92 words per million using CELEX written frequency; Baayen, Piepenbrock, & Van Rijn, 1993) and a low frequency noun (*M*=2.04 words per million). The high and low frequency words were pair-wise matched on length (*M*=7.27 letters; range: 5-10 letters). A separate sample of 22 participants who did not complete the main experiment provided cloze norms. Participants were given each sentence up to the pre-target word and asked to generate the word that was most likely to continue the sentence. The results of the cloze task confirmed that the target words were not predictable from the context. The target word was generated less than 3% of the time, on average (HF target: *M*=2.42%; LF target: *M*=0.72%).

The sentences were presented with normal spacing (*Standard* condition) or in one of three modified spacing conditions (see Figure 1). In the *Numbers* condition, interword spaces were filled by a numeral between 2 and 9. In the *Capitals* condition the spaces were removed but word boundary information was preserved by alternating words in uppercase and lowercase with the constraints that the target word was always in lowercase and the sentence-initial letter was always capitalized. Finally, in the *Unspaced* condition, both the interword spaces and word boundary information were removed. Participants read each target word and sentence frame once but all sentences and targets appeared in all conditions across eight counterbalanced lists.

Apparatus

A desktop-mounted EyeLink 1000 eye tracker was used to record participants' eye movements as they read. Viewing was binocular but gaze position was monitored from the right eye only. The sentences occupied a single line of a ViewSonic P225fb CRT monitor and were presented in size 16 black Courier New font on a light gray background. Viewing was binocular but fixation position was monitored from the right eye. Participants were seated 60 cm from the monitor and a chin and forehead rest was used to minimize head movements. At this distance 2.2 characters subtended 1 degree of visual angle.

Procedure

Participants were instructed to silently read the sentences for meaning and to respond to three-option comprehension questions that required a moderate understanding of the meaning of the sentence which were presented after all practice trials and one-third of experimental trials. The four spacing conditions were presented in separate blocks. The Standard condition was always read first, to provide a pure measure of typical reading uncontaminated by strategic adjustments triggered by the unfamiliar formats. The three modified spacing conditions were then presented in a counterbalanced order. Each block began with a three-point calibration procedure followed by three practice trials and the 30 experimental trials, which were presented in an individually randomized order. At the beginning of each trial a fixation point appeared at the location of the first letter of the sentence. Once a stable fixation was detected on this point, the sentence was displayed or a new calibration procedure was performed if necessary. Mean calibration error was less than

0.5 degrees of visual angle. Participants pressed a key when they finished reading each sentence.

RESULTS

Analyses were conducted on sentence-level measures as well as on reading measures of the low and high frequency target words. The sentence-level measures were *total sentence reading time*, *average fixation duration*, *number of fixations*, *number of regressions*, and *average forward saccade length*. Means for each of these measures are presented in Table 2. The word-level measures were *first fixation duration* (the duration of the first fixation on the target word in first-pass reading, regardless of the number of fixations it received), *gaze duration* (the sum of first-pass fixations on the target word), *total fixation duration* (the sum of all fixations on the target word, including first-pass reading and later rereading). We also analyzed the probability of regressions to the target word (*regressions in*).

Prior to analysis, fixations below 80 ms that were within one letter space of an adjacent fixation were merged with that fixation and remaining fixations below 80 ms or above 1200 ms were eliminated (5.2% of total fixations). For the sentence-level analyses we excluded trials that were inadvertently terminated early by the participant and outlier trials with reading times above 10 seconds (3.4% of trials). For the word-level analyses, trials were eliminated if the participant blinked immediately before or after fixating the target word (5.6% of trials). Target gaze durations above 2000 ms and total durations above 4000 ms were also excluded (<1% of trials). These exclusions left 12250 trials (93.7% of the data) available for analysis.

The data were analyzed by (generalized) linear mixed-effects models (LMM) using the *lme4* package (Version 1.1-10; Bates, Maechler, Bolker, & Walker, 2015) in *R* (Version 3.3.1; R Core Team, 2016). Unless noted, analyses conducted on log-transformed data yielded the same pattern of statistical significance as the analyses based on the raw data reported below. Estimates 1.96 times larger than their standard errors were interpreted as significant at the .05 alpha level because, given the number of observations, the t statistic in LMMs approximates the z statistic.

Standard Condition Analysis

As outlined above, we used a blocked design in which the Standard spaced text condition was always presented first to provide baseline measures uncontaminated by strategies induced by exposure to unspaced formats. To establish the effect of reading and spelling ability on typical spaced text reading, LMMs were first analyzed for each of the sentence- and word-level measures in the Standard condition only. Reading ability and spelling ability were entered into the models as separate, continuous predictors. For the word-level analyses, target word frequency was included as a sum contrast as well as its interactions with both individual difference variables. The models included subject and item random intercepts and item random slopes for reading and spelling ability. The word-level analyses also included subject random slopes for the frequency effect.

At the sentence level, high reading ability was associated with significantly lower total sentence reading time [b=-302.30, SE=132.10, t=-2.29] and fixation count [b=-0.99, SE=0.43, t=-2.29]. There were no effects of reading ability on average fixation duration, regression count, or saccade length [all ts<1.86]. High spelling ability predicted significantly longer saccades [b=0.28, SE=0.12, t=2.31] but there were no significant effects of spelling ability on any other sentence-level measures [all ts<1.60].

There was a significant effect of target word frequency on the majority of word-level measures: first fixation duration [b=12.51, SE=2.19, t=5.72], gaze duration [b=28.14, SE=4.29, t=6.56], and total duration [b=37.86, SE=7.73, t=4.90] were shorter for high-frequency compared to low-frequency words. Readers were also significantly more likely to skip a high frequency target word [b=0.21, SE=0.10, z=2.25] but frequency did not affect landing position on the target word [$|t|<1$] or the probability of a regression to the target [$z<1$]. Mirroring the sentence-level effects, high reading ability was associated with lower fixation durations on the target word [all $|t|$s>2.24]. Better readers were also significantly less likely to regress to the target word [$b=-0.22$, $SE=0.10$, $z=-2.10$] but reading ability did not significantly affect landing position [$t<1$] or skipping [$b=-0.18$, $SE=0.12$, $z=-1.58$], or interact with the frequency effect on any measure [all $|t|$s<1.01 and $|z|$s<1].

High spelling ability predicted more skipping of the target word [$b=-0.39$, $SE=0.12$, $z=-3.11$] and a more rightward landing position on the target [$b=0.19$, $SE=0.07$, $t=2.71$] but spelling ability did not affect regressions in [$b=0.19$, $SE=0.11$, $z=1.74$]. There were no main effects of spelling ability on any of the fixation duration measures on the target word [all $|t|$s<1.68]. However, high spelling ability was associated with a significant reduction in the frequency effect on gaze duration [$b=-7.47$, $SE=3.06$, $t=-2.44$] and total duration [$b=-14.37$, $SE=5.97$, $t=-2.41$]. The Frequency × Spelling interaction was not significant on any other measure [all $|t|$s and $|z|$s<1.63].

Overall, the analysis of the Standard condition showed that reading and spelling ability modulated different aspects of reading behavior. Reading ability, but not spelling ability, predicted the speed of reading normally-spaced text: High reading ability was associated with fewer and shorter fixations and reduced regressions compared to lower reading ability. In contrast, spelling ability selectively predicted saccade measures: Good spellers made longer saccades, landed further into the target word, and showed more word skipping. Spelling ability was also a stronger predictor of lexical processing efficiency: High spelling ability, but not high reading ability, was associated with a reduced word frequency effect. Thus, although spelling ability alone did not account for unique variance in reading speed, this was not due to inefficient reading among good spellers.[1]

Spacing Effects

To analyze the effect of the spacing manipulations, LMMs included successive difference contrasts testing: (1) *Standard* vs. *Numbers* (to assess the effect of filling spaces while maintaining spatial distances between words); (2) *Numbers* vs. *Capitals* (to compare the impact of these different methods of demarcating word boundaries); and (3) *Capitals* vs. *Unspaced* (to assess whether marking word boundaries by case changes reduces the disruptive effects of removing spaces despite the unfamiliar visual format).[2] The two-way interactions between the spacing contrasts and each of the proficiency measures were also included. The word-level analyses additionally included target word frequency and its interactions with the spacing contrasts and the higher order interactions involving the proficiency measures. The models included subject and item random intercepts and subject and item random slopes for the spacing contrasts. The word-level analyses also included subject random slopes for the frequency effect.[3] Means for the sentence-level measures in each spacing condition are presented in Table 2. The (G)LMM coefficients, standard errors, and *t*/*z* values for the fixed effects are reported in Table 3.

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[1] To further investigate the effect of spelling ability on the reading of normally-spaced text, separate analyses were conducted on first-pass sentence reading time (i.e., reading time up until the first encounter with the sentence-final word) and second-pass sentence reading time (i.e., any time spent rereading the sentence after completion of the first pass). The analysis of first-pass reading time exactly mirrored the pattern of significant results from the analysis of total sentence reading time. The analysis of second-pass reading time revealed a significant effect of spelling ability because better spellers spent *more* time rereading the sentence than poorer spellers [b=231.86, SE=83.76, t=2.77]. Reading ability did not significantly affect second-pass reading time [b=-118.67, SE=78.68, t=-1.51]. Thus, the absence of a spelling ability advantage on reading time in the Standard condition was principally due to spontaneous rereading of the sentence, which likely reflects more careful reading among better spellers.

[2] While we acknowledge that alternative contrast schemes might also be appropriate for these data (e.g., Helmert contrasts), we believe that successive difference contrasts best reflected our specific theoretical questions.

[3] The LMMs for regression count, saccade length, and gaze duration failed to converge with this full random effects structure so these models did not include item random slopes.

Comprehension accuracy. Accuracy on the comprehension questions was high (*M*=93.0%, range: 75-100%). A GLMM testing the effects of spacing condition and written language proficiency on comprehension accuracy revealed no differences in comprehension accuracy across the spacing conditions [all *z*s<1]. However, higher reading ability was associated with significantly higher comprehension accuracy [*z*=3.77], which did not interact with spacing condition [all |*z*|s<1]. There were no main effects or interactions involving spelling ability on comprehension accuracy [all |*z*|s<1.37].

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Sentence-level measures. The Standard vs. Numbers comparison revealed that filling interword spaces with numbers resulted in significantly higher sentence reading time, average fixation duration, number of fixations, and significantly shorter forward saccade length [all |*t*|s>9.81] relative to standard spaced text. Somewhat surprisingly, regression count was significantly lower in the Numbers condition than in the Standard condition [*t*=-2.49].[4] The difference between the Numbers condition, in which spaces were filled, and the Capitals condition, in which spaces were removed but word boundaries were marked by presenting alternating words in capital letters, depended on the measure. Reading time and number of fixations were significantly higher in the Numbers condition [|*t*|s>2.05]. However, average fixation duration and number of regressions were significantly higher in the Capitals condition [|*t*|s>2.22]. The Numbers and Capitals conditions did not differ in average saccade length [*t*=-1.14]. The final contrast comparing the Capitals condition, which preserved word boundary cues, with the Unspaced condition, in which word boundary information was

[4] A likely reason for this counterintuitive finding is the blocked order of conditions. The Standard condition was always presented first, followed by a counterbalanced sequence of the remaining conditions. Participants tend to read more slowly and cautiously at the beginning of an experiment compared to later in the experiment, accounting for the higher rate of regressions in the initial Standard condition. Consistent with this interpretation, analyses of the effect of trial order on regressions (see Supplementary Materials) confirmed that regressions decreased significantly over trials in the Standard block (*b*= -0.03, *SE*=0.00, *t*=-8.91) but not in the Numbers block (*b*= 0.01, *SE*=0.01, *t*=1.19).

absent, showed significantly more disruption in the Unspaced condition on all measures [all |*t*|s>9.42].

Paralleling the analysis of the Standard condition, higher reading ability was associated with significantly lower total reading times [*t*=-2.51] and significantly fewer fixations [*t*=-2.50] but reading ability did not affect average fixation duration, regression count, or forward saccade length [all |*t*|s<1.85]. However, there were no significant interactions between reading ability and the spacing contrasts [all |*t*|s<1] indicating that reading ability did not modulate the effects of filling or removing spaces between words. As displayed in Figure 2, which plots model-corrected data (i.e., the effect of reading ability while controlling for spelling ability and vice versa), the benefit of reading ability was constant across conditions. Follow-up analyses, separately for each unsegmented condition, confirmed that the effect of reading ability on sentence reading time was significant in all conditions [all *t*s>2.08]. Similarly, the effect of reading ability on fixation count was significant in the Numbers and Capitals conditions [both |*t*|s>2.52] and marginally significant in the Unspaced condition [*t*=-1.89].

In contrast to reading ability, spelling significantly predicted average forward saccade length, because better spellers made longer saccades than poorer spellers [*t*=2.36], but there were no main effects of spelling ability on any of the other sentence-level measures [all |*t*|s<1.11], However, spelling ability significantly modulated the effects of interword spacing. The Standard vs. Numbers comparison showed that better spellers were significantly less disrupted than poorer spellers by reading filled-space text on sentence reading time, average fixation duration, fixation count, and regression count [all |*t*|s>3.37]. As displayed in Figure 2, the interaction was due to good spellers showing slightly longer reading times in the Standard condition and shorter reading times in the Numbers condition relative to poor spellers.[5] Spelling ability did not significantly interact with the Numbers vs. Capitals contrast on any measure [all |*t*|s<1.65]. However, comparison of the Capitals and Unspaced conditions showed that better spellers were less disrupted than poorer spellers by the absence of word boundary cues in the Unspaced condition on all measures [all |*t*|s>2.44] except saccade length [*t*=1.11]. Follow-up analyses revealed significant effects of spelling ability on sentence reading time, fixation count, regression count, and saccade length in the Unspaced condition [all |*t*|s>2.45].

--- INSERT FIGURE 2 HERE ---

Overall, the sentence-level measures showed strong disruptive effects of the spacing manipulations across the eye movement record. The pattern of effects across conditions clearly revealed that the disruption caused by unspaced text is partly due to being deprived of word boundary information. When boundary information was preserved by inserting numbers or alternating case, the extent of disruption was dramatically reduced relative to Unspaced text. The two methods of preserving word boundary information had slightly different effects on sentence level reading behavior: filling spaces with numbers yielded more fixations and slower overall reading time than alternating case between unspaced words, but the unfamiliar spacing and format of the Capitals condition was associated with longer fixation times and more regressions than the Numbers condition.

Reading and spelling ability showed quite different relationships to the sentence-level measures. Higher reading ability was associated with faster overall reading but did not modulate the effects of spacing. In complete contrast, spelling ability was unrelated to overall performance, apart from saccade length, but strongly modulated the spacing effects across the reading record: better spellers were less affected by the spacing manipulations than poorer

[5] The (nonsignificant) increase in reading time for better spellers in the Standard condition was due to a greater likelihood of rereading the sentence. However, this was not the source of the interaction with the Standard vs. Numbers contrast because the effect was also significant when the analysis was restricted to first-pass reading time [*b*=-208.70, *SE*=52.65, *t*=-3.96].

spellers, showing both less disruption from filling spaces with numbers relative to standard spaced text, and less disruption in the Unspaced condition which deprived them of both spaces and the word boundary cues that were available in the Capitals condition. Analysis of the word-level data provides further insight into the source of these differences.

--- INSERT TABLE 4 HERE ---

Word-level measures. Means for the target word-level measures in each spacing condition are presented in Table 4. The (G)LMM coefficients, standard errors, and *t*/*z* values for the fixed effects are reported in Table 5. Because the target word was rarely skipped in the unsegmented conditions (see Table 4), we do not report a GLMM analysis of this measure.

--- INSERT TABLE 5 HERE ---

Consistent with the sentence-level results, the Standard vs. Numbers contrast showed that filling spaces with numbers resulted in significantly higher fixation durations on the target word [all ts>8.50]. Readers' saccades landed significantly further into the target word in the Standard spacing condition [t=-12.34] but they were more likely to regress to the target word than in the Numbers condition [z=-5.20]. The Numbers vs. Capitals comparison showed no difference in first fixation duration [t<1] but gaze and total durations were significantly longer in the Capitals condition [ts>2.27]. The Capitals condition was also associated with saccades landing closer to the word beginning [t=-6.46] as well as more regressions to the target word [z=5.92]. The Capitals vs. Unspaced contrast showed that the absence of word boundary cues in the Unspaced condition was associated with longer fixation durations and higher regression rates [all ts>3.82 and z=2.77]. Saccades also landed closer to the word beginning in the Unspaced condition [t=-4.46].

Target word frequency significantly interacted with spacing condition, suggesting that word recognition was impaired in unfamiliar spacing conditions. The Standard vs. Numbers contrast showed that filled-space text resulted in a larger frequency effect on gaze and total duration [both *t*s>2.94; but this effect was not significant in the analysis of log gaze duration: *b*=0.01, *SE*=0.01, *t*=1.23]. First fixation duration showed a significant effect in the opposite direction because the frequency effect was slightly larger in the Standard than in the Numbers condition [*t*=-2.03]. The Capitals condition produced a larger frequency effect than the Numbers condition on gaze and total duration [both *t*s>3.16] suggesting that the type of word boundary cue affected fixation durations on low- but not high-frequency words. Finally, the Unspaced condition elicited a larger frequency effect than the Capitals condition on total duration only [*t*=3.06; but, again, this effect did not reach significance in the analysis of log total duration: *b*=0.03, *SE*=0.02, *t*=1.42]. Thus, the average word-level data closely mirror the sentence-level effects and confirm that the differences between the spacing conditions are at least partly attributable to increased difficulty in lexical processing when spaces between words are unavailable.[6]

The main effects of reading ability broadly paralleled the sentence level analyses by showing that higher reading ability was associated with significantly shorter gaze and total duration [both |*t*|s>2.51]. Reading ability did not affect first fixation duration [*t*=-1.70], saccade landing position [*t*<1], or regressions in to the target word [*z*<1], nor did it modulate the size of the frequency effect on any measure [all |*t*|s<1.67]. There were no interactions between reading ability and spacing condition on any fixation duration measure [all |*t*|s<1.91]. However, the regression probability measure showed a significant interaction between reading ability and the Standard vs. Numbers contrast [*z*=2.48], reflecting the lack of an effect of reading ability on regressions in the filled-space condition [*z*<1]. The Spacing

[6] Interpretation of the interactions with word frequency are qualified by the fact that two of interactions were not significant in the analysis of log transformed measures. The convergence of these two discrepancies between the outcomes of analyses conducted on raw and log transformed data suggest that the larger frequency effects observed in the unfamiliar formats may be primarily due to long fixations, which are truncated by log transformation. All of the other effects reported were significant in analyses of both raw and log transformed data, indicating that the choice of dependent variable does not influence interpretation of the effects of other factors (Lo & Andrews, 2015).

condition × Frequency × Reading ability interactions were not significant on any measure [all $|t|$s and $|z|$s<1.25].

Unlike the sentence-level measures, spelling ability yielded significant main effects on all fixation duration measures [all $|t|$s>2.49] reflecting shorter fixations by better spellers. Higher spelling ability was also associated with saccades landing significantly further into the target word [t=3.21] and a reduced frequency effect on all duration measures [all $|t|$s>2.73].

Spelling ability also participated in several significant interactions between spelling ability and spacing condition (see Figure 3). Participants with higher spelling ability were significantly less disrupted than poorer spellers by the lack of word spaces in the Numbers condition relative to the Standard condition on all measures [all $|t|$s>2.05 and z=-2.50] except landing position [t<1]. Spelling ability did not modulate the difference between the Numbers and Capitals condition on any measure [all $|t|$s and z<1]. Finally, the Capitals vs. Unspaced contrast showed that better spellers experienced significantly less disruption from completely removing word boundary cues on total duration only [t=-3.13]. Follow-up analyses revealed significant effects of spelling ability on target word duration measures in all three unsegmented conditions [$|t|$s>2.40], confirming that the beneficial effects of spelling ability on fixation duration were specific to the modified spacing conditions. The Spacing × Frequency × Spelling ability interactions were not significant on any measure [all $|t|$s and $|z|$s<1.93].

--- INSERT FIGURE 3 HERE ---

Overall the word-level analyses converge with the sentence-level analyses in showing that spelling ability predicted the extent of disruption to reading from denying word-spacing information. High reading ability predicted faster reading and less rereading on average. High spelling ability predicted longer saccades, more skipping, and more efficient word level processing. However, spelling ability was also selectively associated with smaller effects of interword spacing modifications. At the word level, the greater resilience to filling spaces with numbers and of removing spaces but preserving boundary information in the Capitals condition shown by better spellers was evident across the eye movement record but the beneficial effect of spelling ability on reading completely unspaced text was limited to total duration.

DISCUSSION

The major goal of the present study was to investigate individual differences in eye movement control during skilled reading when readers were exposed to an unfamiliar, unsegmented layout of the text. More specifically, we examined how reading and spelling ability affect use of interword spaces and word boundary cues during reading. However, before discussing the contribution of individual differences, we first compare the average results for our novel blocked design with those of past studies on spacing effects.

The average results converge with previously reported findings of the effect of removing or replacing interword spaces on reading (Epelboim et al., 1994, 1997; Malt & Seamon, 1978; McGowan et al., 2014; Paterson & Jordan, 2010; Perea & Acha, 2009; Perea et al., 2015; Pollatsek & Rayner, 1982; Rayner et al., 1998; Sheridan et al., 2013, 2016; Spragins et al., 1976; Yang & McConkie, 2001). Compared to normally-spaced text, the sentence-level analyses showed that sustaining reading comprehension for unsegmented text required readers to make more and longer fixations, more regressive fixations, and shorter saccades. Furthermore, the word-level analyses showed that word identification was more difficult without interword spaces: The frequency effect was larger and saccades landed closer to the beginning of the word in the unsegmented conditions.

Across the different unsegmented conditions, readers experienced the most severe disruption in the Unspaced condition which eliminated both spaces and information about word boundaries. Consistent with previous findings using alternations of type font (Perea &

Acha, 2009) and color (Perea et al., 2015), the disruptive effects of removing spaces was significantly reduced in the Capitals conditions which also removed spaces but preserved word boundary information by alternating case between successive words. The average total sentence reading time was 16.7% slower in the Capitals than the Standard condition, a smaller disruption than Perea and Acha's (2009) finding of a 31% increase in total reading time for alternating**bold** text, but larger than the 4.7% cost reported by Perea et al. (2015) for alternatingcolor relative to a standard spaced alternating color condition. The Numbers condition also replicated previous findings with similar filled-space text (e.g., Sheridan et al., 2013, 2016) in showing substantially less disruption in total reading time relative to Standard text (19.1%) than Unspaced text (34.1%). The novel direct comparison of the Numbers and Capitals conditions revealed small but significant differences that varied across the reading measures. The Numbers condition yielded less efficient sentence level performance, reflected in significantly longer reading times and more fixations, but word level fixations were shorter and regression rates lower than in the Capitals condition. However, the word frequency effect was also smaller in the Numbers than in the Capitals condition, implying that the type of word boundary cue had more of an effect on first-pass reading of low- than high-frequency words. Thus, word identification appears to be more difficult when spaces are removed rather than filled, presumably because of effects of lateral masking of initial and final letters (Perea et al., 2015) combined with the unfamiliar visual format created by case alternation.

In the present study, the order of the spacing conditions was blocked, in contrast to previous studies which have typically intermixed spaced and unspaced trials. The consistency of the average results for our unsegmented conditions with previously reported findings implies that the effect of spacing on reading is not solely due to the effects of trial-to-trial variability in format. Given the significant individual differences observed in the present data, further research is required to determine whether this factor modulates the role of reading and/or spelling ability on unspaced text reading.[7]

As outlined in the Introduction, two contrasting predictions were made concerning the impact of individual differences in language proficiency on spacing effects. Given that the complex perceptual, motor, and cognitive processes required for effective reading comprehension appear to operate automatically and rely heavily on parafoveal processing to guide eye movement control, higher proficiency readers might have been expected to show *greater* disruption from removing spaces from text. The results provided no evidence to support this prediction. Rather, higher proficiency was associated with *less* disruption from unspaced text reading. However, the individual difference results revealed an intriguing dissociation between the effects of reading and spelling ability.

Reading ability was strongly associated with both sentence and word level measures of reading efficiency in all conditions: better readers made fewer fixations and spent less time reading the sentence and fixating the target word. Reading ability predicted better comprehension of the experimental sentences. However, reading ability did not interact with the effects of spacing. Good and poor readers showed equivalent disruption from unsegmented text. Critically, the absence of significant interactions between reading ability and spacing cannot be attributed to the inadequacy of passage comprehension as a predictor of eye movements given its strong relationship to the majority of reading measures across all spacing conditions.

In contrast to reading ability, spelling ability did not predict faster reading of normally spaced text. Rather, spelling ability selectively and consistently modulated saccade length

[7] Analyses of the effects of trial and block order (see Supplementary Materials) revealed minimal evidence that practice within an experimental session affected reading of text in unfamiliar formats or that individual differences in proficiency modulate practice effects. Practice effects were primarily restricted to the Standard condition, presumably because this block was always presented first. The only evidence of individual differences in practice effects was an effect of reading ability in the Capitals condition because better readers benefitted more from practice in this condition compared to the Unspaced condition.

and the extent of disruption caused by filled-space and unspaced text. This aligns with previous evidence that reading and spelling ability make independent contributions to parafoveal processing of normally spaced text: Spelling ability selectively predicted effects of the orthographic identity and length of a parafoveal preview on target processing (Veldre & Andrews, 2015b), while reading comprehension but *not* spelling ability predicted parafoveal semantic preview effects (Veldre & Andrews, 2016b).

The fact that spelling ability selectively modulated the impact of removing interword spacing implies that the reading decrement caused by unspaced text is due, in part, to lexical processing difficulty. Higher spelling ability was associated with a reduced frequency effect across all fixation duration measures of target word processing that was maintained across the spacing conditions. This suggests that better spellers were more efficient at retrieving low frequency words and that this lexical processing advantage was sustained in unsegmented text. Although reading and spelling ability were moderately correlated, the fact that spelling ability predicted *differences* in reading behavior among the spacing conditions that were not accounted for by reading ability implies that the interactions of spelling ability with the spacing manipulations are due to unique variance in spelling ability that is not shared with reading comprehension ability. The selective effects of spelling ability therefore likely stem from systematic variability in the precision of readers' lexical representations, consistent with the lexical quality hypothesis (Andrews, 2008, 2012; Perfetti, 2007). These data imply that high quality lexical representations inoculate the reader against the lexical processing difficulty caused by removing and distorting word boundary cues.

The causal link between lexical quality and eye movements is not necessarily straight-forward. Some researchers have argued that poor eye movements *cause* reading deficits, citing evidence that inefficient oculomotor control in poor and disabled readers extends to non-reading tasks (e.g., Kulp & Schmidt, 1996; Powers, Grisham, & Riles, 2008). However, such findings have proved difficult to replicate (e.g., Hutzler, Kronbichler, Jacobs, & Wimmer, 2006; Kirkby, Blythe, Drieghe, & Liversedge, 2011) and there is little evidence to suggest that training eye movements has any effect on reading ability (e.g., Rawstron, Burley, & Elder, 2005; Rayner, 1985; Stanovich, 1986). Nevertheless, this does not rule out the potential for a bi-directional relationship between lexical quality and eye movements during reading. For instance, readers with incomplete word knowledge are thought to use contextual prediction to identify words from partial orthographic cues (e.g., Frith, 1980, 1985; Holmes & Carruthers, 1998; Holmes & Castles, 2001). This word identification strategy may be reflected in reduced processing of parafoveal information to guide eye movements during reading, and lead to the tendency for saccade landing positions to cluster nearer the beginning of words, rather than in more 'optimal viewing positions' (O'Regan & Jacobs, 1992) toward the centre of the word, a finding that was observed among poorer spellers in the present study. With reading experience, continued reliance on a contextually-driven strategy and limited orthographic analysis impedes the development of precise, fully-specified word representations in lexical memory, reinforcing reliance on context to supplement partial orthographic cues. While this 'partial-cue strategy' (Frith, 1985) is effective in many reading tasks, it does not foster the development of automatic word identification processes because readers must supplement incomplete orthographic input with top-down information from the sentence or discourse context. Such a strategy is also likely to increase the difficulty of extracting words from a string of letters in which word boundaries are not marked. The impact of poor spellers' imprecise lexical representations may therefore be magnified in unspaced text which reduces the effectiveness of a partial orthographic strategy by disrupting selection of the word level units on which it depends. The lack of word boundary information forces them to extract complete orthographic information in order to determine where to move the eyes next. In contrast, good spellers can use their precise word-specific knowledge to facilitate extraction of word units from unsegmented text. The major advantage of this enhanced capacity may lie in the benefits it confers for adapting reading behavior to the requirements of specific formats.

A number of features of the present data suggest that the benefits associated with precise lexical knowledge derive from more effective extraction of words from unspaced text. While higher reading ability was associated with reduced reading times at both the sentence and word level, better spellers only showed shorter fixation times on word-level measures, in the unsegmented text conditions. However, they consistently made longer saccades and landed further into the target word. Better spellers also showed a smaller effect of word frequency across all conditions suggesting that the higher quality lexical representations assumed to be indexed by superior spelling support more efficient lexical retrieval. Given that the *magnitude* of the reduction in the frequency effect was not significantly affected by spacing, the spelling benefit appears to reflect a greater capacity to *locate* the orthographic units to use for lexical retrieval even when spaces are not available to support this chunking.

The systematic effect of spelling ability on saccadic landing position suggests that the location of word units occurred parafoveally. Moreover, higher spelling ability appears to foster the extraction of lexical units regardless of whether or not alternative cues are provided to delineate word boundaries. Further research using the boundary paradigm to assess preview effects in unspaced text (Sheridan et al., 2016) will be necessary to confirm whether the spelling ability effects are due to differences in parafoveal processing. However, given previous evidence of selective effects of spelling on parafoveal orthographic preview benefits, (Veldre & Andrews, 2015a, 2015b), parafoveal processing efficiency is a likely candidate to account for the spelling effects in unsegmented text.

In addition to more precise word-specific knowledge, good spellers may also make use of richer implicit orthographic knowledge and superior meta-linguistic awareness of abstract spelling rules (Kreiner, 1992; Kreiner & Gough, 1990) to assist in the location of word boundaries. Better spellers demonstrate greater sensitivity to particular context-specific regularities, such as the fact that the same vowel is spelled differently depending on the consonantal context (Treiman & Kessler, 2006) and may be more sensitive to letter sequences and higher-order orthographic clusters that are permissible in English (Omrod, 1990; Pacton, Perruchet, Fayol, & Cleeremans, 2001). High spelling ability is also associated with superior morphographic knowledge, such as the ability to quickly identify prefixes and suffixes that provide reliable cues to word beginnings and endings (Fischer, Shankweiler, & Liberman, 1985). Such rich knowledge about the orthographic structure of words might facilitate the segmentation of words in unspaced text by enhancing sensitivity to illegal or infrequent letter clusters that commonly occur across word boundaries and contribute to better spellers' greater resilience to the elimination of spacing information to delineate words.

Conclusion

The present findings add to a mounting body of evidence demonstrating systematic individual differences among skilled adult readers in the processes underlying sentence reading. They make a novel contribution to this evidence by investigating how skilled readers use interword spaces and word boundary cues during online reading and adapt to unfamiliar unspaced text. The results showed that, although measures of reading comprehension predicted overall reading speed and fluency, spelling ability uniquely predicted readers' resilience to the disruptive effects of unspaced text on the efficiency of eye movement control during reading, implying that the locus of spacing effects is lexical processing difficulty, and that precise lexical knowledge can partly ameliorate this difficulty. These findings converge with previous evidence in demonstrating that precise word-specific knowledge facilitates reading by enhancing the extraction of lexical information during online reading, even in unfamiliar text formats.

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FIGURE CAPTIONS

Figure 1. An example sentence in each of the spacing conditions used in the experiment.

Figure 2. Sentence reading time (upper panels) and number of fixations (lower panels) for each of the spacing conditions, separately for low and high reading ability (left) and low and high spelling ability (right). The data are LMM-adjusted values, partialing out the effects of the other proficiency measure. All analyses used continuous measures of reading and spelling but the data are plotted separately for low and high ability groups, based on median splits, for the purpose of visualization. Error bars are 95% confidence intervals.

Figure 3. Target word gaze duration (upper panels) and total fixation duration (lower panels) in each of the spacing conditions, separately for low and high reading ability (left) and low and high spelling ability (right). The data are LMM-adjusted values, partialing out the effects of the other proficiency measure. All analyses used continuous measures of reading and spelling but the data are plotted separately for low and high ability groups, based on median splits, for the purpose of visualization. Error bars are 95% confidence intervals.