Effects of Intra-word and Inter-word Spacing on Eye Movements during Reading: Exploring the Optimal use of Space in a Line of Text

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Running Head: Eye movements and spacing effects

Abstract

Two eye movement experiments investigated intra-word spacing (the space between letters within words) and inter-word spacing (the space between words) to explore the influence these variables have on eye movement control during reading. Both variables are important factors in determining the optimal use of space in a line of text, and fonts differ widely in how they employ these spaces. Prior research suggests that the proximity of flanking letters influences the identification of a central letter via lateral inhibition or crowding. If so decrements in intra-word spacing may produce inhibition in word processing. Still other research suggests that increases in intra-word spacing can disrupt the integrity of word units. In English, inter-word spacing has a large influence on word segmentation and is important for saccade target selection. The results indicate interplay between intra and inter word spacing which influence a font's readability. Additionally, these studies highlight the importance of word segmentation processes and have implications for the nature of lexical processing (serial vs. parallel).

While there have been a considerable number of experiments (see Rayner, 1998, 2009 for reviews) devoted to understanding how various lexical variables influence eye movements during reading, there have been far fewer studies examining the influence of typographical and font variables. It is quite clear that very difficult to encode fonts will lead to slower reading, and concomitantly to longer eye fixations, shorter saccades, and more regressions (Rayner & Pollatsek, 1989; Rayner, Pollatsek, Ashby, & Clifton, 2012; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006). In general, however, the consensus view seems to be that as long as type font, type size, and length of lines are at all reasonable, reading will proceed quite normally because lexical processing of the words in the text drives the eyes (Morrison & Inhoff, 1981; Rayner & Pollatsek, 1989). Because of this general view, until recently, the number of studies examining typographical variables has been quite sparse. However, recently a number of studies dealing with the effect of typographical variables on eye movements during reading have appeared. Indeed, Slattery and Rayner (2010) demonstrated that even subtle font differences lead to effects on eye movements, and that these effects can interact with higher level cognitive variables like word frequency. In the present article, we examined how a different type of typographical variable, the spacing between letters, influences reading.

Calculating the number of characters (N_C) on a line of text is a trivial matter. The relevant variables for the calculation are the length of the line (L), and the width of the individual characters (W_C). Assuming a fixed width font for simplicity, results in equation 1.

Equation 1: $N_C = L/W_C$

However, for our discussion, it is also necessary to differentiate between *characters* and *letters*. Here we will refer to a letter as the colored area of a (non-space) character that is distinct from the background. Therefore, a character contains the letter and space surrounding this letter which is indistinguishable from the background. Two letters (eg. xy) within a word will be separated by intra-word space; the sum of the space to the right of the leftmost letter and the space to the left of the rightmost letter. The importance of this intra-word space (S_1) can be seen through the application of kerning. Kerning is the process of adjusting the intra-word space between certain letters so that the letters within a word all appear uniformly spaced. For instance, in the uppercase word *VAST*, the letters *V* and *A* are placed closer to each other than the other letters are. In fact, in x, y coordinate space, the x value of the rightmost point of the letter *V* is greater than the x value for the leftmost point of the letter *A*.

Of course, not every character contains a letter. The inter-word space (S_2) is a character that is completely indistinguishable from the background. These inter-word spaces are far more distinct in English (and other alphabetic) text than the intra-word spaces between letters within a word are and so play a crucial role in the number of letters that can fit on a line of text. For a fixed width font, this results in equation 2 where W_L is the width of the letter and N_W is the number of words on the line:

Equation 2: $N_L = L – (S_2 * (N_W -1))/(W_L + S_1)$

While it is a trivial matter to calculate the number of characters or letters that can fit on a line of text, it is far less trivial to determine how to optimize the variables in equation 2 for the purpose of reading efficiency. The present work outlines the relevant factors involved in determining such optimal values for two of the variables involved in this equation: intra-word spacing and inter-word spacing.

Intra-word spacing effects:

Intra-word spacing can influence reading processes in a number of ways. First, it is well-known that crowding from flanker letters influences how quickly and accurately a central letter can be identified (Bouma, 1970; Chung, Levi, & Legge, 2001; Erikson & Erikson, 1974). If letter trigrams are pushed closer together, masking from the exterior flanker letters makes it harder to identify the central letter, whereas increasing the space between these letters reduces the amount of crowding making it easier to identify the central letter. In fact, increased spacing between letters also results in increases in perceived letter size (Skottun & Freeman, 1983). There are three main characteristics of visual crowding. The first is that effects of crowding increase with increasing distance of the target from the fovea (Bouma, 1970). The second is that the effect of flankers is asymmetric with the outer or more eccentric flanker exerting a greater crowding effect than the less eccentric inner flanker (Petrov, Popple, & McKee, 2007). Finally, the zone of crowding is not circular but instead exhibits a radial-tangential anisotropy, such that flankers positioned along the radial axis from the fovea to the target will produce more crowding than those placed tangentially to this axis (Toet & Levi, 1992). Recently, Nandy and Tjan (2012) show that all of these characteristics of crowding can be explained as a consequence of saccades confounding the statistics of natural images. However, identifying a central letter is very different from identifying a word. For instance, with central letter identification tasks, performance improves to an asymptote as the flankers are moved further from the central letter. However, with word identification tasks like lexical decision and categorization, inhibition occurs both with reduced intra-word spacing and with intra-word spacing that is increased beyond some critical point (Chung, 2002; McLeish, 2007; Paterson & Jordan 2010; Pelli, Tillman, Freeman, Su, Berger, & Majad, 2007; Vinckier, Qiao, Pallier, Dehaene, & Cohen, 2011; Risko, Lanthier, & Besner, 2011). While it is clear that increasing intra-word spacing beyond some critical value (two or three character spaces) will disrupt reading, it is far less clear what effect will occur for more subtle increases. There are reports of facilitation in lexical decision tasks with subtle increases to intra-word space (Perea, & Gomez 2012). However, Perea, Moret-Tatay, and Gomez (2010) noted, the results of studies that use subtle manipulations of increased intra-word spacing are somewhat inconsistent--probably due to the fact that the amount of space added between letters varied across the studies as did the fonts used in the studies. Fonts can differ quite a bit in their default intra-word spacing. For instance, Times New Roman has less spacing than `Courier New`. Therefore, if there exists some optimal value for intra-word spacing, then one might expect studies using different fonts may yield inconsistent results.

Changes in intra-word spacing, unless compensated for with changes in inter-word spacing, will also lead to changes in the number of letters that can fall within high acuity foveal vision during a single fixation. For single word presentation tasks like lexical decision, naming, and categorization this is only a minor issue. However, for normal reading which involves a considerable amount of parafoveal preprocessing of text (Rayner, 1998, 2009; Schotter, Angele, & Rayner, 2012), such changes could add up to large effects as upcoming words are pushed further and further from fixation.

Some studies have explored the effect of adding or deleting spaces within text during normal reading by examining eye movements. In a clever experiment, McDonald (2006) varied the letter width and intra-word space such that all the words in a sentence would subtend the same visual angle. He found clear differences between target words that differed in number of letters (so either a 6 letter word or an 8 letter word occupied the same amount of space in the sentence). Specifically, the more letters in the word, the more fixations that were made on the word and the longer were the fixation times on the word. Of course, this manipulation confounds the number of letters in a word with letter width and spacing and he noted that the most plausible explanation for the findings was that the longer words were subject to a greater degree of visual crowding. Going in the other direction, Paterson and Jordan (2010) found a detrimental effect of intra-word spacing on eye movements. However, in their experiment the smallest addition to intra-word spacing added an extra space b e t w e e n e a c h l e t t e r (as in the prior three words) and this most likely disrupted the overall integrity of the words in the sentences. In fact, Paterson and Jordan also reported that the effect of word frequency was larger for all increased spacing conditions relative to the standard spacing control condition. From this result they argue that the increased spacing interfered with normal word processing.

Inter-word spacing effects:

Word identification is paramount during reading. As such it is crucial that when we read a line of text, we are able to identify the beginnings and endings of individual lexical items; a process referred to as word segmentation. A number of studies have reported substantial reductions in reading rate for English text when inter-word spaces are removed (Morris, Rayner, & Pollatsek, 1990; Perea & Acha, 2009; Pollatsek & Rayner, 1982; Rayner, Fischer, & Pollatsek, 1998; Rayner, Yang, Schuett, & Slattery, 2013; Sheridan, Rayner, & Reingold, 2013; Spragins, Lefton, Fisher, 1976). However, at least one study reports a more modest reduction in reading rate for text without spaces (Epelboim, Booth, & Steinman, 1994). This reduction in reading rate is greater for lower frequency words than it is for higher frequency words, and greater for contextually constraining text than for less constraining text, suggesting that the lack of inter-word spacing interferes with normal word identification processes. It is interesting to note that not all written languages use inter-word spaces. For instance, neither Thai nor Chinese text has inter-word spaces. However, despite this lack of inter-word spacing, word segmentation is just as important in these languages (see Li, Rayner, & Cave, 2009). For instance, text with added inter-word spaces has been found to increase reading rate for both Thai (Kohsom & Gobet, 2007; Winskel, Radach, & Luksaneeyanawin, 2009) and Chinese (Hsu & Huang, 2000a, 2000b) compared to traditional text without such word spaces. Additionally, novel Chinese words are learned more efficiently when presented in sentences with inter-word spaces (Blythe, Liang, Zang, Wang, Yan, Bia, & Liversedge, 2012). However, other studies have reported faster reading of text with added inter-word spaces only relative to a condition with spaces added at non-word boundaries (Bai, Yan, Liversedge, Zang, & Rayner, 2008) with no difference in reading rate between traditional non-spaced text and text with inter-word spaces. More recently, it has been shown that people learning Chinese as a second language benefit from added inter-word spaces (Shen, Tian, Yang, Cui, Bai, Yan, Liversedge, & Rayner 2012). Thus readers of Thai and Chinese appear to be segmenting characters into words, similar to readers of alphabetic languages, but are normally making use of cues other than inter-word spaces for these segmenting processes.

Inter-word spaces also have the effect of reducing lateral inhibition of the first and last letters of words. This may be largely responsible for the important role that first and last letters of words play during word recognition (Davis, 2010; Gomez, Ratcliff, & Perea, 2008; Jordan, 1990, 1995). Thus we might expect that increasing intra-word spacing would reduce this lateral interference leading to faster reading rates especially for fonts with small default inter-word spacing.

Inter-word spaces may play a role beyond just word segmentation and lateral inhibition of word beginning and ending letters. They may also influence the targeting and or accuracy of saccades within the oculomotor system. Inter-word space helps to break up the line of text into distinct light and dark patches. This low frequency spatial information can be used even in parafoveal vision to help target saccades to areas that are more optimal for word identification. With normally spaced text, a reader's first fixation on a word tends to be just left of word center (Rayner, 1979). This location is referred to as the preferred viewing location (PVL). However, with unspaced text readers initial fixation on a word tends to be shifted more toward the beginnings of words (Rayner et al., 1998). However, there are of course errors in saccade planning and execution. Often these errors are large enough to result in mislocated fixations—fixations that land on unintended words. Such mislocated fixations have been estimated to occur on as many as 15% to 20% of all reading saccades (Drieghe, Rayner, & Pollatsek, 2008; Engbert & Nuthman, 2008). These mislocated fixations would slow the reading process by placing the fovea in suboptimal locations. Increased inter-word spacing may serve to reduce the number of mislocated fixations yielding more efficient reading. Recent work by Engbert and Krügel (2010) suggests that readers are using Bayesian estimation of word centers when targeting saccades. From such a Bayesian framework, increasing inter-word spacing may aid in the accurate targeting of saccades toward word centers by reducing observational error in the estimation of target distance.

There is however at least one potential inhibitory effect that we expect from increasing inter-word spaces. Adding additional space between words, unless offset by decreases in intra-word spacing, will push upcoming words further from the current fixation (i.e. further into the parafovea or periphery where visual acuity drops sharply and crowding effects increase). This may reduce the ability to gain useful previews of upcoming words (Rayner, 1998, 2009; Schotter et al., 2012). Thus, finding an optimal amount of inter-word space will be a balancing act similar to finding an optimal amount of intra-word space.

In the experiments reported here, we explored how the use of space on a line of text influences eye movements during reading. In Experiment 1 we systematically varied the amount of intra-word spacing (by increasing and decreasing the space between letters). In Experiment 2 we pit intra-word and inter-word spacing against each other in a unique manipulation that allowed us to test both the balance of these factors as well as some controversial assumptions about the nature of lexical processing during reading.

Experiment 1

In Experiment 1, we investigated the role that intra-word spacing played with regards to eye movements during reading. We explored the influence of letter spacing by adjusting the tracking between characters within a font. We employed four levels of spacing: reduced by half a pixel, normal, increased by half a pixel, and increased by a full pixel. Figure 1 shows a sentence across these four spacing conditions for each font. This manipulation is far more subtle than the one used by Paterson and Jordan (2010), and similar to the one used by Perea et al. (2010). Note that, this manipulation applied to all characters including the inter-word space. Thus the relation between intra-word and inter-word spacing was the same across the four levels of spacing.

Insert Figure 1 here

Different fonts, even when rendered at the same point size, vary on a multitude of dimensions, including intra-word and inter-word spacing. Therefore, in addition to the above-mentioned spacing manipulation, we also explored the influence of this spacing manipulation across two different fonts (Times New Roman and Cambria). Both of these fonts are proportional width, both have serifs, and both are highly familiar to readers. However, at 10 points, Cambria has more intra-word spacing than Times New Roman. Therefore, it is possible that the spacing manipulation we employed in Experiment 1 would affect these two fonts differently. An added benefit of using Times New Roman is that this is the font used by Perea et al. (2010), and Perea and Gomez (2012) who found facilitation with increased intra-word spacing in single word recognition.

Finally, previous studies that have manipulated frequency and spacing and which have reported inhibition from increased intra-word spacing have also reported interactions between spacing and frequency with increased spacing interfering with low frequency words more than high frequency ones. However, the studies that have reported facilitation have not found interactions between frequency and spacing. Therefore, in order to explore how the bottom up spacing manipulation was influenced by top down processing, we embedded either a low or a high frequency word in each sentence. To the extent that the intra-word spacing manipulation interferes with normal word processing, we would expect an interaction between spacing and word frequency.

Method

Subjects

Thirty-two undergraduate students at the University of Massachusetts at Amherst received course credit or were paid $7.00 for their participation. All subjects were naïve concerning the purpose of the experiment, were native speakers of English, and had either normal or corrected to normal vision.

Apparatus

An SR Research Eyelink 1000 eyetracker was used to record subjects' eye movements with a sampling rate of 1000 Hz. Subjects read sentences on a 19-inch Viewsonic VX 924 LCD monitor at its native resolution of 1280 by 1024 pixels. Viewing was binocular, but only the movements of the right eye were recorded. Viewing distance was approximately 50 cm.

Materials.

Ninety-six experimental sentence frames, were adapted from Sereno and Rayner (2000) and Slattery, Pollatsek, and Rayner (2007). Each frame contained one of a pair of frequency manipulated target words, thereby creating 192 unique experimental sentences. The high frequency members of these target word pairs averaged approximately 138 occurrences per million, and the low frequency members averaged approximately 17 occurrences per million in the HAL database (Burgess, 1998; Burgess & Livesay, 1998) according to the English Lexicon Project website (Balota, Yap, Cortese, Hutchison, Kessler, Loftis, et al., 2007)[1]. The average length of the target words was 5.8 characters (range: 3-11) and was matched between the high and low frequency words. An example of a sentence with its high and low frequency version appears below (1: high frequency, 2: low frequency), with the target word appearing in italics[2].

1. They shouted at the *driver* who wildly cut them off.
2. They shouted at the *cabby* who wildly cut them off.

The sentences were presented as black letters on a white background in either 10 pt Cambria or Times New Roman font with Microsoft ClearType sub-pixel rendering (for more on ClearType, see Larson 2007; Slattery & Rayner, 2010). The sub-pixel rendering allowed us to adjust the letter spacing of characters in small increments. It is perhaps easiest to explain the ClearType sub-pixel rendering with an analogy to greyscale rendering. Imagine that we rendered a letter I in greyscale and that the width of this letter was one and a half pixels. To make the letter appear that it was more than one pixel but less than two pixels wide, we would adjust the level of grey of the second pixel (for which there are 256 levels). The darker grey this second pixel, the wider the letter would appear. With ClearType sub-pixel rendering we can adjust the level of each of the three colored sub-pixels of an LCD monitor (each with 256 levels of color) giving us more precision in the appearance of the rendered letters. Figure 1 above shows the 4 levels of character spacing we employed for Experiment 1: reduced by half a pixel, normal, increased by half a pixel, and increased by a full pixel(for reference, one pixel subtended 0.032° of visual angle). The distance between levels of this spacing variable was therefore constant allowing us to examine trends analyses for our data (see results below).

On average, target words subtended 1.42 degrees of visual angle in the normal spacing condition for both the Cambria and Times New Roman fonts. However, due to various differences between these fonts related to proportional character widths and inter-word spacing, there were slight differences in the visual angle subtended by the entire sentences. The average sentence length in the normal condition was 10.95° of visual angle for the Cambria sentences and 11.14° for Times New Roman. This difference was approximately the size of a single character; however it was statistically significant, $p < .05$.

Procedure.

At the start of the experiment, subjects were familiarized with the experimental apparatus. Next, a calibration procedure was initiated which required subjects to look at a random sequence of fixation points presented horizontally across the middle of the computer screen. This procedure was repeated during a validation process, and the average error between calibration and validation was calculated. If this error was greater than .4° of visual angle the entire procedure was repeated. At the start of each trial, a black square (0.8 degrees of visual angle) appeared on the left side of the computer screen, which coincided with the left side of the first letter in the sentence. Once a stable fixation was detected within this area, the sentence replaced it on the screen. All sentences were presented vertically centered on the computer monitor. Subjects were instructed to read silently for comprehension and to press a button on a keypad when they finished reading the sentence. Comprehension questions appeared on the screen after a third of all the items. These yes/no questions required the subjects to respond via button press. Latin square counterbalancing assured that each subject saw an equal number of sentences in each experimental condition, no subject saw any sentence frame more than once, and over all subjects each sentence was seen equally often in each experimental condition. Sentence order was randomized for each subject.

Results

We analyzed a number of dependent measures and will break up our results into two main sections. The first of these will consist of global measures of sentence reading: mean fixation duration, number of fixations, total sentence reading time, and comprehension question accuracy. For the calculation of the global reading dependent measures, we averaged over the independent variable of target word frequency. Each of these global reading measures was submitted to two 2 (font: Cambria vs. Times New Roman) X 4 (spacing: -1/2 pixel, normal, +1/2 pixel, +1 pixel) ANOVAs; one with subjects as a random effect variable and one with items as a random effect variable. We also report F tests for the trends analyses of the spacing variable. These analyses test whether the data over the spacing variable fit linear, quadratic, or cubic trends. This is important given the subtle nature of our manipulation. For instance, there may be no significant difference between consecutive levels of the spacing variable, but there may be a highly significant linear trend (slope significantly different than 0) in the spacing data when performance over levels is examined. Such trends are of paramount importance to the current research. Counterbalance list was added as a dummy variable (Pollatsek & Well, 1995).

The second section will consist of eye movement measures for target word processing: first fixation duration (the duration of the first fixation on the target word), gaze duration (the sum of all first pass fixations on the target word), skipping rate, and the length of the critical saccade that landed on (or beyond) the target word. Each of these target word dependent measures was submitted to two 2 (font: Cambria vs. Times New Roman) X 4 (spacing: -1/2 pixel, normal, +1/2 pixel, +1 pixel) X 2 (word frequency: high vs. low) ANOVAs; one with subjects as a random effect variable and one with items as a random effect variable. As with the global measures, we again examine the trends analyses for spacing. Counterbalance list was added as a dummy variable.

Prior to analysis, fixation durations less than 80 milliseconds were removed from the record (less than 1% of fixations). Trials with blinks on or near the target word or fixations longer than 1000 milliseconds on the target word were excluded from analysis as were trials with more than 2 blinks during sentence reading. These trials accounted for 2.6 percent of the total trials and were evenly distributed across experimental conditions. Additionally, trials with fewer than 4 or more than 20 fixations were also excluded from analysis (0.8% of trials).

Global Measures

Accuracy to the comprehension questions was very high (mean of 92%) and was unaffected by experimental condition, $ps > .20$. Therefore, any effects seen in the fixation time measures cannot be explained by a speed accuracy trade-off.

Arguably the most diagnostic measure of font readability in the current study is total sentence reading time, as it encompasses all the potential costs of the various manipulations. This measure indicated that sentences presented in Cambria (1884 ms) were read faster than those presented in Times New Roman (1938 ms), $F1(1,16) = 9.91$, $MSE = 27153$, $p < .01$; $F2(1,80) = 17.55$, $MSE = 47897$, $p < .001$. The effect of spacing was also significant (-1/2: 1923 ms; 0: 1862 ms; +1/2: 1911 ms; +1: 1909 ms), $F1(3,48) = 2.857$, $MSE = 16911$, $p < .05$; $F2(3,240) = 2.80$, $MSE = 57598$, $p < .05$, but more importantly there was a significant quadratic trend of spacing, $F1(1,16) = 6.71$, $MSE = 12388$, $p < .05$; $F2(1,80) = 5.10$, $MSE = 47656$, $p < .05$. This trend indicated that the normal, unadjusted spacing was optimal for the fonts and spacing levels chosen in the study. The font by spacing interaction was not significant $Fs < 1$.

Insert Figure 2 about here

The average fixation durations while reading the sentences were significantly influenced by both spacing and font. Mean fixation duration was shorter for sentences presented in Cambria (243 ms) than for those in Times New Roman (247 ms), $F1(1,16) = 11.20$, $MSE = 68$, $p < .005$, $F2(1,80) = 10.43$, $MSE = 230$, $p < .005$. Mean fixation duration was also influenced by spacing, $F1(3,48) = 22.59$, $MSE = 109$, $p < .001$, $F2(3,240) = 26.07$, $MSE = 281$, $p < .001$. Trends analyses indicated that the spacing effect was highly linear (-1/2: 253 ms; 0: 247 ms; +1/2: 241 ms; +1: 240 ms), $F1(1,16) = 41.98$, $MSE = 167$, $p <.001$, $F2(1,80) = 76.48$, $MSE = 268$, $p < .001$, as mean fixation duration decreased with increasing spacing. There was no interaction between font and spacing, Fs < 1.

Insert Figure 3 about here

On average, readers fixated sentences presented in Cambria 7.68 times and fixated those presented Times New Roman 7.89 times, F1(1,16) = 10.08, MSE = .22, p < .01; F2(1,80) = 7.44, MSE = .78, p < .01. Spacing also significantly influenced the number of fixations that sentences received, F1(3,48) = 9.17, MSE = .23, p < .001; F2(3,240) = 6.95, MSE = .79, p < .001. For the number of fixations (-1/2: 7.64; 0: 7.58; +1/2: 7.93; +1: 7.99), there was a significant linear trend of spacing, F1(1,16) = 19.91, MSE = .22, p < .001; F2(1,80) = 14.82, MSE = .77, p < .001, as well as a cubic trend, F1(1,16) = 8.20, MSE = .15, p < .05; F2(1,80) = 3.65, MSE = 1.76, p = .060. Again, the interaction between font and spacing did not approach significance, Fs < 1.

Insert Figure 4 about here

Target Word Analyses

In order to examine how the experimental variables of font and spacing influenced word processing we analyzed fixation measures on the high and low frequency target words that were embedded in the sentence frames. On average, these target words were fixated during first pass reading 84.2% of the time. On the remaining 15.8% of the time, the eyes fixated beyond the target word without having directly fixated on the target itself. These cases are classified as skips of the target word whether or not the target word is later fixated as the result of regressive eye movements. Word frequency significantly influenced this skipping behavior, F1(1,16) = 5.21, MSE = 1.9, p < .05; F2(1,80) = 4.16, MSE = 6.3, p < .05, as high frequency target words were skipped 17% of the time and low frequency targets were skipped 14% of the time. There was also an effect of font that was only fully significant in the subjects analysis, F1(1,16) = 9.13, MSE = 1.0, p < .01; F2(1,80) = 3.65, MSE = 6.4, p = .06, as target word skipping rate was higher with Cambria (17%) than Times New Roman (14%). However, there was no effect of spacing, Fs < 1, nor was there a significant linear, quadratic, or cubic trend of spacing on skipping rates, Fs < 1. There were also no significant interactions between any of these variables, Fs < 1.

Insert Table 1 about here

To further examine the effect of spacing on eye movements, we calculated the mean landing position for the initial fixations on these targets as a percentage of target word length. This measure indicated that on average subjects fixated these target words slightly to the left of word center (0.45), replicating prior research (McConkie, Kerr, Reddix, & Zola, 1988; Rayner, 1979). However, there were no significant effects of any of the experimental variables on this measure (all ps > .10). The fact that the spacing manipulation did not influence word skipping behavior or initial fixation landing site illustrates that the saccadic system is capable of rapidly adjusting to serve the goals of reading. Unsurprisingly, the length (in visual angle) of the first saccade into or beyond the target word was highly influenced by spacing (-1/2: 2.05°; 0: 2.16°; +1/2: 2.25°; +1: 2.41°), F1(3,48) = 29.67, MSE = .10, p < .001; F2(3,240) = 26.81, MSE = .34, p < .001. Trends analyses show that this effect was highly linear in nature, F1(1,16) = 53.34, MSE = .17, p < .001; F2(1,80) = 56.69, MSE = .50, p < .001. The distribution of these critical saccade lengths are displayed in Figure 5. There was also an effect of font on the length of these critical saccades, F1(1,16) = 4.52, MSE = .15, p < .05; F2(1,80) = 6.37, MSE = .35, p < .05, with these critical saccades being .07 degrees larger, on average, with Cambria than with Times New Roman. Recall that there was a slight difference in the horizontal extent of the two fonts used in this study with Cambria being slightly narrower than Times New Roman. Therefore, this effect is in the opposite direction predicted by the difference in the size of the fonts, suggesting that Cambria was easier to process than Times New Roman.

Insert Figure 5 about here

The duration of the initial fixation on the target words was influenced by spacing, $F1(3,42) = 3.57$, $MSE = 1325$, $p < .05$; $F2(3,123) = 2.95$, $MSE = 4018$, $p < .05$, as these initial fixations tended to decrease in duration with increasing spacing[3] (-1/2: 263 ms; 0: 259 ms; +1/2: 249 ms; +1: 251 ms). These initial fixations were also influenced by target word frequency, $F1(1,14) = 8.65$, $MSE = 1191$, $p < .05$; $F2(1,41) = 7.25$, $MSE = 4995$, $p < .05$, with longer durations occurring on low frequency (261 ms) than high frequency (251 ms) words. There was a font by word frequency interaction but only in the items analysis, $F1 < 1$; $F2(1,41) = 3.92$, $MSE = 6.3$, $p < .05$. This interaction appears to be due to a smaller frequency effect with the Cambria font. However, we don't place much weight in this interaction due to the non-significant subjects analysis (see also footnote 3). No other interactions approached significance, $ps > .12$.

Unlike first fixation durations, gaze durations were not influenced by spacing, $ps > .25$. However, there was still a highly robust effect of word frequency, $F1(1,14) = 22.56$, $MSE = 1688$, $p < .001$; $F2(1,41) = 20.64$, $MSE = 6933$, $p < .001$, as gaze durations were longer on low frequency (297 ms) than on high frequency (278 ms) target words. Gaze durations did not significantly differ between the two fonts, $F1(1,14) = 1.40$, $MSE = 4758$, $p > .25$; $F2(1,41) = 2.99$, $MSE = 7069$, $p > .09$, nor were there any significant interactions between any of the three variables, $ps > .16$.

Discussion

There were a number of important findings from Experiment 1 with regards to the optimal use of space in a line of text. First these results reconfirm that subtle low level font characteristics do influence eye movement behavior during reading (Slattery & Rayner 2010; Rayner et al., 2006; Rayner, Slattery, & Bélanger, 2010). We found that wider spacing results in shorter average fixation durations consistent with the linear facilitative effects reported by Perea et al. (2010) and Perea and Gomez (2012) using the lexical decision task. While not statistically significant from the other spacing conditions, gaze durations on target words presented in Times New Roman were shortest in the +1/2 pixel condition, which also agrees with Perea et al. (2010) and Perea and Gomez (2012). Also similar to Perea et al. (2010) we failed to find any interaction between word frequency and intra-word spacing. Additionally, this effect of spacing did not interact with word frequency in any of our dependent measures indicating that more subtle adjustments to intra-word spacing do not disrupt the integrity of word units the way that larger adjustments do. However, this facilitative effect on fixation durations was offset by the trends in the number of fixations. Total reading time, which is a direct combination of average fixation duration and number of fixations, was shortest in the unmodified spacing condition, replicating RSVP reading results (Chung, 2002), suggesting that font designers are doing a relatively good job at selecting these default intra-word spacing values. The increase in total sentence reading time associated with changes from default intra-word spacing was asymmetrical with the largest increase coming from the reduced intra-word spacing condition which caused both an increase in average fixation duration and number of fixations.

The current results also highlight the flexibility of the oculomotor system to rapidly adjust to the spacing manipulation employed in Experiment 1 for the purpose of reading. Target word skipping, which is highly influenced by the number of letters in a word (Rayner & McConkie, 1976; Brysbaert, Drieghe, & Vitu, 1998), was uninfluenced by the spacing variable. This argues that word skipping behavior is influenced more by word processing than by the horizontal extent of the skipped word. Spacing influenced initial fixation duration on target words, with shorter fixations for larger spacing, but did not influence gaze durations as the refixation probability associated with spacing mitigated the effect that had been present in initial fixation durations. This further highlights the higher level cognitive impact upon oculomotor behavior during reading. That is, despite the undeniable and rapid low level influences of font spacing on fixation durations, higher level cognitive influences help to ensure that the eyes remain on words long enough to accomplish the goal of successful reading.

Other effects of interest were that Cambria consistently outperformed Times New Roman in metrics of readability. It resulted in shorter fixation durations, fewer fixations, and shorter total reading times than Times New Roman with no decrement in comprehension. As Cambria is a newer font created for use on computer monitors this finding should be welcomed by font designers and taken as an indicator of their relative success.

Experiment 2

In Experiment 1, the relative space between letters and words remained constant over the spacing conditions. One drawback of that manipulation is that words will be closer to each other in the smaller spacing conditions than in the larger spacing conditions. Thus, it is possible that parafoveal processing of the upcoming word was influenced by its proximity to the currently fixated word. In Experiment 2, we employed a modified spacing manipulation in which the space between word beginnings was held constant over the intra-word spacing conditions (see also Rayner et al. 2010). This manipulation removed space between letters within a word (reduced intra-word spacing) and placed that space after the word (increased inter-word spacing). Therefore, each word of a sentence began at the same location regardless of spacing condition (see Figure 6). This manipulation has the added benefit of allowing us to directly test aspects of visual crowding on reading. Visual crowding occurs when objects are closer together than the critical spacing, which depends on eccentricity of the objects from fixation (Levi, 2008; Pelli & Tillman, 2008). The further the eccentricity of the objects, the greater the critical spacing will be. However, in Experiment 1 intra-word spacing (the space between letters within a word) of parafoveal letters was confounded with the eccentricity of these letters (see Figure 1). This confound with eccentricity should have acted to reduce the letter crowding effect within words in the reduced intra-word spacing condition. In Experiment 2, we controlled for eccentricity over the letter spacing conditions.

Insert Figure 6 about here

This novel manipulation has a few important implications for reading and font development. First, if letter perception, which is known to be influenced by visual crowding, is driving the eyes during reading, we should see a marked increase in fixation durations and reading times for the reduced intra-word/increased inter-word spacing condition (from here on referred to as the adjusted spacing condition) in Experiment 2 compared to the normal spacing condition. However, for the purpose of reading we suspect that words are more important objects than letters. This may seem like an impossible stance as words are built from a combination of letters. We are not advocating that letters are unimportant. As Pelli, Farell, and

Moore (2003) convincingly demonstrated, word recognition cannot occur under conditions in which the word's letters are not separately identifiable. However, as long as the letters are identifiable we would argue that it is the properties of words and their recognition that influence eye movements during reading. For instance, the words *slide* and *idles* both contain the same letters but arranged in different orders thereby making two different words. These two words differ in their frequency of usage (*slide* is roughly 120 times more frequent than *idles*), their phonological structure (*slide* has one syllable while *idles* has two), and morphological structure, as well as in the manner in which they can be used in the English language. We would argue therefore that while successful letter perception is a necessary step in reading, the bottleneck in reading performance is with word recognition. If, as we suspect, words are the important processing unit for reading we might expect that in Experiment 2 the adjusted spacing condition should result in improved reading performance compared to the normal spacing condition. The reason for this counterintuitive prediction is that the adjusted spacing condition will not only have reduced intra-word spacing, but will also have increased inter-word spacing. This increased inter-word spacing should help with word segmentation processes, result in less lateral inhibition of word initial and final letters, and improve oculomotor targeting.

Second, a major current controversy in reading is centered on whether lexical processing of words occurs in serial or is parallel in nature with multiple words being accessed at the same time (Reichle, Liversedge, Pollatsek, & Rayner, 2009). It has now been shown repeatedly that reducing intra-word spacing reduces a word's readability and that this effect of crowding is a function of a words eccentricity from fixation. Thus, we can be confident that crowding will hamper the lexical processing of a word in the parafovea. If normal reading involves parallel lexical processing of the fixated word and words in the parafovea, reading should be greatly disrupted under the adjusted spacing conditions of Experiment 2, which presents the parafoveal words with reduced intra-word spacing while controlling for word eccentricity. However, if normal reading involves the serial lexical identification of words with a limited role of lexical processing in the parafovea, we would expect little to no difficulty with this reduced intra-word spacing condition. Note, that the serial lexical processing prediction does not suggest that parafoveal processing is unimportant, only that there is a limited role for *lexical* processing of parafoveal words.

Method

Subjects

Sixty-four undergraduate students at the University of California, San Diego received course credit or were paid $10.00 for their participation. As with Experiment 1, all subjects were naïve concerning the purpose of the experiment, were native speakers of English, and had either normal or corrected to normal vision.

Materials.

Subjects read a new set of one hundred and eight experimental sentences. These sentences were presented as black letters on a white background in one of two 14 pt fonts. We chose to use a larger size font than in Experiment 1 to be more consistent with the font sizes typically used in psycholinguistic studies and to better explore landing site distributions which were flatter than expected in Experiment 1. In order to explore a wider range of fonts we chose two that hadn't been used in Experiment 1: Georgia which is a proportional width serif font and very similar to the two fonts used in Experiment 1 (see Figure 7), and Consolas which is a fixed width san-serif font similar to the fonts used in traditional psycholinguistic eye movement studies. Another important difference between these fonts is that Consolas has a considerably larger default inter-word space while only slightly larger intra-word spacing. The average sentence length for the

Georgia sentences was 555 pixels and for the Consolas sentences it was 690 pixels, $p < .001$. Font was a between subject variable in Experiment 2 so that we would have more observations per condition per item than we had in experiment 1 (see footnote 3).

Insert Figure 7 Here

Each sentence contained one of a pair of frequency manipulated target words. The high frequency members of these target word pairs averaged approximately 171 occurrences per million, and the low frequency members averaged approximately 4 occurrences per million in the HAL database (Burgess, 1998; Burgess & Livesay, 1998) according to the English Lexicon Project website (Balota, et al., 2007). The average length of the target words was 7.3 characters (range: 5-10) and was matched between the high and low frequency words.

Apparatus and Procedure.

As with Experiment 1, an SR Research Eyelink 1000 eyetracker was used to record subjects' eye movements with a sampling rate of 1000 Hz. Subjects read sentences on a 19-inch Viewsonic VX 922 LCD monitor (a newer version of the monitor used in Experiment 1) at its native resolution of 1280 by 1024 pixels. Viewing was binocular, but only the movements of the right eye were recorded. Viewing distance was approximately 50 cm. The procedure was identical to Experiment 1.

Results

We analyzed the same dependent measures as in Experiment 1, and will again break up our results into global measures of sentence reading, and standard eye movement measures for target word processing. Each of the global reading dependent measure was submitted to 2 (font: Georgia vs. Consolas) X 2 (spacing: adjusted vs. normal) ANOVAs; one with subjects as a random effect variable and one with items as a random effect variable. Each of the target word dependent measure was submitted to 2 (font: Georgia vs. Consolas) X 2 (spacing: adjusted vs. normal) X 2 (word frequency: high vs. low) ANOVAs; one with subjects as a random effect variable and one with items as a random effect variable. Note that font was a between subject variable but a within item variable for these analyses. Additionally, counterbalance list was added as a dummy variable as with the analysis for Experiment 1. Prior to analysis, fixation durations less than 80 milliseconds were removed from the record (less than 1% of fixations). The same criteria used for trial exclusion in Experiment 1 were used which resulted in 2.5 percent of the total trials which were evenly distributed across experimental conditions.

Global Measures

As with Experiment 1, there was no evidence of a speed accuracy trade-off as the accuracy to the comprehension questions was very high (mean of 94%) and was unaffected by experimental conditions, $ps > .20$.

Insert Table 3 about here

Readers in Experiment 2 spent 98 ms longer reading sentences presented in Consolas (2035 ms) than those presented in Georgia (1937 ms) though this effect was only significant in the items analysis, $F1 < 1$; $F2(1,104) = 21.94$, $MSE = 73931$, $p < .001$, The main effect of spacing did not approach significance nor did the interaction between spacing and font, $ps > .30$.

The mean fixation durations while reading the sentences were significantly influenced by font, F(1,56) = 7.02, MSE = 1924, p < .05; F2(1,104) = 224.43, MSE = 202, p < .001, being 14 ms longer for Georgia (236 ms) than for Consolas (222 ms). Mean fixation duration was also influenced by spacing, F1(1,56) = 16.40, MSE = 43, p < .001, F2(1,104) = 13.09, MSE = 187, p < .001, contrary to the results of Experiment 1; this effect was due to mean fixation durations being 4 ms shorter in the adjusted spacing condition (227 ms) than in the normal spacing condition (231 ms). There was also a significant 5 ms interaction between font and spacing, F(1,56) = 6.48, MSE = 43, p < .05; F2(1,104) = 5.11, MSE = 187, p < .05, as the benefits of the adjusted spacing were largely limited to the Georgia font. This is of interest as the Georgia font had both smaller default intra-word and inter-word spacing than Consolas.

As with Experiment 1, the average number of fixations required to read the sentences was also influenced by the font in which they were presented, F1(1,56) = 4.01, MSE = 15, p = .05; F2(1,104) = 221.98, MSE = 0.86, p < .001, as sentences presented in Georgia were read with fewer fixations on average (8.12) than those presented in Consolas (9.10). The spacing manipulation did not significantly influence the number of fixations required to read the sentences, F1(1,56) = 1.39, MSE = .26, p > .20; F2(1,104) = 2.64, MSE = 0.74, p > .10, nor was there a significant font by spacing interaction, Fs < 1

Target Word Analyses

Another benefit of the spacing manipulation used in Experiment 2 was that it allowed us to examine eye movement measures of target word processing on the same exact region of the computer monitor across the different spacing conditions (see Figure 6). Therefore, any difference in eye movement measures on these regions would be unrelated to the physical size or location of these regions themselves. Such differences could have an impact on measures like skipping rates.

Insert Table 4 about here

The target word regions were fixated during first pass reading on 89.6% of trials. On the remaining 10.4% of trials, there was no direct fixation on the target word region prior to fixating a region of the sentence beyond (to the right of) the target word, which we denote as a skip. These target word skips were more likely when the frequency of the target was high (12.1%) than when it was low (5.6%), F1(1,56) = 33.53, MSE = .24, p < .001; F2(1,104) = 15.89, MSE = 1.81, p < .001. Target word skipping was also more likely with Georgia (13.2%) than with Consolas (7.5%), F1(1,56) = 8.72, MSE = 2.42, p < .005; F2(1,104) = 66.11, MSE = 1.06, p < .001. There was no main effect of spacing on the skipping rate, F1(1,56) = 1.12, MSE = 0.37, p > .25; F2(1,104) = 1.81, MSE = .83, p > .15. However, there was an interaction between spacing and font that was marginal by subjects and significant by items, F1(1,56) = 3.72, MSE = .37, p = .059; F2(1,104) = 4.50, MSE = 1.12, p < .05. This interaction was due to skipping being marginally more likely with the Georgia font when the spacing was adjusted (14.4%) than when it was normal (12.1), t1(31) = 1.80, p = .081; t2(107) =1.89, p = .062, but with the Consolas font, skipping was less likely with the adjusted (7.2%) than with the normal (7.8%) spacing though this difference was not significant, ts < 1.

To further examine the effect of spacing on eye movements, we again calculated the mean landing position for the initial fixations on these targets as a percentage of target word length (the size of the equated region of analysis for target word fixations). As with Experiment 1, subjects fixated slightly to the left of the center of target words (.41). Unlike Experiment 1, this measure was significantly influenced by word frequency as initial landing position was further toward the right with high frequency words (.43) than with low frequency words (.40), $F1(1,56) = 8.98$, $MSE = .003$, $p < .005$; $F2(1,104) = 10.42$, $MSE = 0.01$, $p < .005$. There was also an effect of the spacing manipulation that was marginal in the subjects analysis but significant by items, $F1(1,56) = 3.29$, $MSE = .003$, $p = .075$; $F2(1,104) = 10.42$, $MSE = 0.007$, $p < .005$, as target words in the adjusted spacing condition were fixated closer to the beginning of the target word region (0.41) than those in the unadjusted spacing condition (0.42). This spacing effect on landing position, which is admittedly quite small, and while not fully significant, may suggest that readers are attempting to target the center of the visible words as these word centers are located further to the left in the adjusted spacing condition than in the unadjusted spacing condition (see Figure 6). There was no significant effect of font nor were there any significant interactions between any of the variables, $ps > 0.25$. First fixation durations on the target word were strongly influenced by word frequency, $F1(1,56) = 49.25$, $MSE = 356$, $p < .001$; $F2(1,104) = 40.01$, $MSE = 1408$, $p < .001$, with low frequency words (239 ms) being fixated longer than high frequency words (223 ms). First fixation durations were also 9 ms longer with the Georgia font than with Consolas but this difference was only significant in the items analysis, $F1(1,56) = 2.69$, $MSE = 1881$, $p = .107$; $F2(1,104) = 21.45$, $MSE = 769$, $p < .001$. Finally, there was an 8 ms font by spacing interaction that was marginal by subjects and significant by items, $F1(1,56) = 3.97$, $MSE = 273$, $p = .051$; $F2(1,104) = 4.02$, $MSE = 726$, $p < .05$, as the adjusted spacing resulted in numerically shorter first fixation durations for the Georgia font, but numerically longer first fixation durations for Consolas. This interaction mirrors the one reported above for mean fixation durations. Neither the main effect of spacing, nor any other interactions approached significance, $ps > .15$.

Gaze durations were longer on low frequency target words (292 ms) than on high frequency ones (254 ms), $F1(1,56) = 153.05$, $MSE = 609$, $p < .001$; $F2(1,104) = 64.27$, $MSE = 4771$, $p < .001$. Gaze durations were shorter for target words displayed in Georgia (268 ms) than those presented in Consolas (270 ms), though this was only significant in the items analysis, $F1(1,56) = 1.01$, $MSE = 5620$, $p > .30$; $F2(1,104) = 40.01$, $MSE = 1408$, $p < .001$. This effect while not fully statistically significant is of particular interest because it is in the opposite direction of the effect of font on the first fixation duration measure, an indication that the target words are being re-fixated more during first pass reading when presented in Consolas. The main effect of spacing was not significant, $Fs < 1$. However, there was also a marginal interaction between spacing and word frequency, $F1(1,56) = 3.20$, $MSE = 607$, $p = .079$; $F2(1,104) = 3.67$, $MSE = 2041$, $p = .058$, as gaze durations on high frequency words were numerically shorter with adjusted spacing (250 ms) than with normal spacing (257 ms) but gaze durations on low frequency words were numerically longer with adjusted spacing (294 ms) than with normal spacing (290 ms). There were no other significant effects on gaze durations, $ps > .10$.

The critical saccade length was significantly influenced by font, $F1(1,56) = 7.14$, $MSE = 1.13$, $p < .01$; $F2(1,104) = 134.69$, $MSE = .20$, $p < .001$, as the visual angle subtended by these saccades was .36 degrees larger in the wider Consolas font, than in Georgia (see Figure 8). These saccades were also larger with high (3.20°) than with low (3.07°) frequency target words, $F1(1,56) = 27.55$, $MSE = .04$, $p < .001$; $F2(1,104) = 23.92$, $MSE = .16$, $p < .001$. Finally, these critical saccades were .08 degrees larger under the adjusted spacing conditions, $F1(1,56) = 6.83$, $MSE = .05$, $p < .05$; $F2(1,104) = 8.20$, $MSE = .13$, $p < .01$, despite the fact that we controlled for the location of the beginning of all words in the sentences across these spacing conditions. There were no significant interactions between any of these variables, ps > .17.

Discussion

The results of Experiment 2 replicate many of the experimental findings in the field of eye movements and reading. There were highly significant word frequency effects on fixation durations and skipping probabilities (see Rayner, 1998, 2009 for reviews). At first blush it may seem that the relatively small number of statistically significant effects of reduced intra-word spacing from Experiment 2 may indicate that intra-word spacing is relatively unimportant with regards to reading. However, we would strongly disagree with such a conclusion. First, given the existing literature and the results of Experiment 1 there were many reasons to expect very strong interference effects with the reduced intra-word spacing condition of Experiment 2. Despite this, there were no significant interference effects found in Experiment 2. Instead we found a significant benefit from this reduced intra-word spacing (and increased inter-word spacing) condition in the form of shorter fixation durations. When viewed together with the results of Experiment 1 this facilitative effect must be due to the increased inter-word spacing that resulted form the novel manipulation used in Experiment 2. We take this as strong evidence in favor of words rather than letters being the important objects in normal reading. Additionally, the interactions of font and spacing for both the mean fixation duration and first fixation duration measures indicate that optimality of intra and inter-word spacing is font specific. The facilitation due to the adjusted spacing condition was largely limited to the Georgia font. This font had smaller default values of inter-word spacing relative to the Consolas font. Therefore, for Georgia, there was more room for improvement with added inter-word spacing. It is likely that the default inter-word spacing for Consolas is large enough that any potential benefits to further increasing this space are offset by potential penalties for decreasing the intra-word spacing.

Additionally, this result may be difficult to reconcile with models of eye movement control in reading that assume parallel lexical identification of words. That is, such models would have to account for two empirical findings: (1) reduced intra-word space hinders word identification as a function of eccentricity, and (2) reduced intra-word spacing when accompanied by increased inter-word spacing does not slow reading and actually leads to shorter average fixation durations. Therefore, models, which predict that a substantial amount of lexical processing occurs parafoveally, would seem to predict that if parafoveal word processing were made more difficult, there should be considerable impairments to normal reading. We will have more to say about this in the General Discussion that follows.

General Discussion

We conducted two eye movement studies to examine the influence that intra-word spacing (space between letters within a word) and inter-word spacing (the space between words within a line of text) have on reading. The results of these experiments highlight the distinction between these two types of textual spacing. Experiment 2, in conjunction with Experiment 1, provides useful information on the topic of optimal spacing within and between words on a line of text. It was clear from Experiment 1 that intra and inter word spacing could have large impacts on reading performance. However, it wasn't clear whether these effects were due to the visual crowding of the letters within the words, the words within the line of text, or some combination of these factors. The specific crowding manipulation used in Experiment 2 placed the letter and word crowding explanations against each other. The results of this second experiment indicate that word spacing can have a profound influence on reading performance. Fixation durations were actually shorter in the reduced intra-word (increased inter-word) spacing condition than in the normal spacing condition of Experiment 2. This is indeed the opposite effect obtained in Experiment 1 with reduced intra-word spacing. The difference between the studies is that in Experiment 1 the reduced intra-word spacing condition also had reduced inter-word spacing while in Experiment 2 the reduced intra-word spacing condition increased inter-word spacing to control for the eccentricity of parafoveal words. The interaction in Experiment 2 between font and spacing on average fixation duration further supports the idea that the facilitative effects of spacing in this experiment were due to increased inter-word spaces. This interaction indicated that the facilitative effects were greater for the Georgia font than the Consolas font. This is important because the default (normal) inter-word spacing for the Georgia font was considerably smaller than the default inter-word spacing for the Consolas font (i.e. there was more potential for improvement with Georgia).

These inter-word spacing effects agree with other reports of facilitation due to increased space between words (Drieghe, Brysbaert, & Desmet, 2005; Inhoff et al., 2000; Paterson & Jordan, 2010). However, they appear to be at odds with the reports that reduced intra-word spacing is inhibitory (Pelli et al., 2007; Perea et al., 2010; Perea & Gomez, 2012; Yu et al., 2007). How can these seemingly contradictory findings be explained? We believe that the answer lies in the word segmentation processes that occur in normal reading. The vast majority of the studies that report inhibitory effects from reduced intra-word spacing involved single word presentation[4] often with presentation of word order being scrambled. In such pseudo-reading tasks, word segmentation is unnecessary. However, in normal reading for comprehension, these word segmentation processes are crucial. It is likely then that reduced intra-word spacing does result in some amount in visual crowding for letters, which causes delays in word recognition. In studies using single word presentation, the only applicable spaces are intra-word and inhibitory effects of letter crowding are more straightforward. However, in studies that involve reading sentences or larger passages, these inhibitory effects of intra-word crowding can be offset by the facilitation of important segmentation processes that transform the string of letters in a line of text into a string of recognizable words.

The facilitative effects of increased inter-word spacing with decreased intra-word spacing that occurred in Experiment 2 also make sense from the standpoint of the E-Z Reader model of eye movement control (Pollatsek, Reichle, & Rayner, 2006; Rayner, Ashby, Pollatsek, & Reichle, 2004; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2007; Reichle, Rayner, & Pollatsek, 1999, 2003). In this model, the majority of the lexical processing associated with a given word occurs while that word is fixated[5]. While a word is fixated, the effects of letter crowding would be trivial as eccentricity is at a minimum. However, the model also assumes that processing of the low spatial frequency information in the text occurs over a much larger area and serves to guide saccade planning to word units. As such this process would be expected to benefit from increased inter-word spacing for the purpose of word segmentation. Though simulations will be needed to verify that E-Z Reader is capable of capturing this data pattern. In contrast to the E-Z Reader model, the SWIFT model of eye movement control (Engbert, Nuthmann, Richter, & Reinhold, 2005; Laubrock, Kliegl, & Engbert, 2006; Richter, Engbert, & Kliegl, 2006) assumes that lexical processing can occur for multiple words in parallel with a larger amount of the processing for a word occurring in parafoveal vision. The current findings seem harder to reconcile with such a model, as the adjusted letter spacing should have caused considerable crowding for parafoveal words, thus reducing a readers ability to lexically process them in their parafovea. Simulations will be required to determine if It may be possible for SWIFT to predict a decrease in lexical parafoveal processing without any decrement in reading rate. One possibility is that under such reading conditions, lexical processing shifts from the parafovea to the fovea and reading becomes more serial. However, that explanation invites the following question: If reading under these reduced intra-word/increased inter-word conditions results in serial lexical identification with shorter average fixation durations, why would cognitive systems ever develop such a parallel lexical processing ability in the first place?

As with most research, these findings raise more new questions than they answer. The fact that intra-word spacing can be reduced without hindering reading, so long as inter-word spacing is also increased, opens up a slew of possibilities regarding spacing optimization. For instance, do function words (e.g. *it, in, on, by*…) require as much inter-word spacing as content words (i.e. *pony, charm, freedom*…)? Are some words more susceptible to the inhibitory effects of reduced intra-word spacing (letter crowding). Can inter-word spacing be adjusted to better represent the phrase structure of sentences thereby allowing for easier syntactic parsing? Clearly more research is needed to explore how textual spacing can be optimized for the purposes of fluent reading. However, as the current studies show, such research is likely to bear fruit.

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Footnotes

1. The reason that these frequencies are approximations is that there is some uncertainty about the size of the HAL corpus with estimates ranging from 131 million words to around 400 million words. The 400-word estimate, which can be found at http://elexicon.wustl.edu/News.html, is the most recent we are aware of, and the one assumed here. However, it should be noted that the absolute value of these estimates is of less importance to the current study than the difference between the estimates which is unaffected by the exact size of the corpus.

2. The target words did not appear in italics during the experiment.

3. Note that the degrees of freedom for these tests reflect listwise deletion due to missing data. There was greater missing data in the items analysis due to the fact that an item would be seen only twice in any given condition.

4. Yu et al. 2007 did use sentence stimuli in one of their spacing experiments. However, their manipulation of spacing was the same as our Experiment 1 spacing manipulation, which confounded intra-word and inter-word spacing.

5. This is an oversimplification of the model, and does not consider word skipping. However, word skipping occurs largely on short high frequency function words that are often highly predictable from sentence context so for our current argument it seems a fair oversimplification.

Table 1. Target word processing measures Experiment 1

Font	Cambria		Times New Roman	
Spacing	-1/2		0	
Spacing	Adjusted	Normal	Adjusted	Normal
Mean fixation duration	233 (3.8)	239 (4.0)	221 (3.8)	222 (4.0)
Number of fixations	8.16 (.34)	8.09 (.35)	9.14 (.34)	9.05 (.35)
Total reading time	1921 (97)	1953 (102)	2033 (97)	2027 (102)

Note: Duration measures are given in milliseconds. Standard errors are shown in parenthesis.

Table 3. Target word processing measures Experiment 2

Font		Georgia		Consolas	
Spacing		Adjusted	Normal	Adjusted	Normal
Skipping rate	High	15.8 (1.7)	13.7 (1.6)	8.9 (1.7)	10.0 (1.4)
	Low	12.9 (1.6)	10.5 (1.4)	5.4 (1.6)	5.6 (1.6)
First fixation duration	High	226 (5)	231 (4)	218 (5)	216 (4)
	Low	239 (5)	246 (5)	237 (5)	235 (5)
Gaze duration	High	244 (7)	256 (6)	256 (7)	258 (6)
	Low	286 (9)	286 (8)	301 (9)	294 (8)
Critical saccade length	High	3.09 (.11)	2.98 (.10)	3.40 (.11)	3.34 (.10)
	Low	2.93 (.11)	2.84 (.09)	3.28 (.11)	3.24 (.09)
Landing site	High	0.42 (.01)	0.43 (.01)	0.42 (.01)	0.42 (.01)
	Low	0.39 (.01)	0.42 (.01)	0.40 (.01)	0.41 (.01)

Note: All duration measures are given in milliseconds, skipping rate is shown as a percentage, saccade length is in visual angle and landing site is given as a percentage of word length. Standard errors are shown in parenthesis.

Figure 1. Example stimuli from Experiment 1 showing the four levels of spacing with Cambria sentences appearing above Times New Roman ones.

Figure 2. Total sentence reading times for Experiment 1. Error bars represent the within subject standard error for the spacing effect.

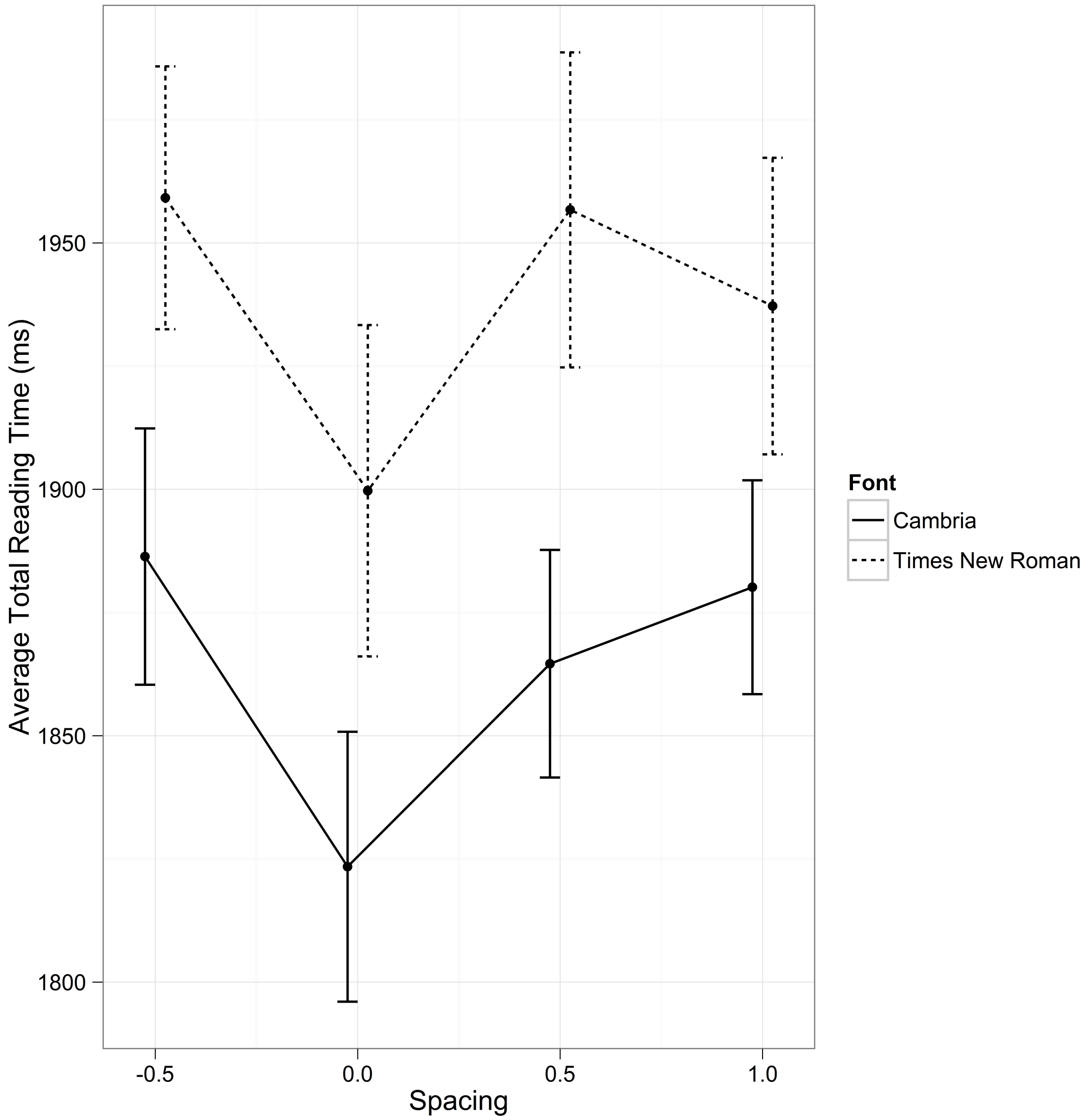

Figure 3. Average fixation durations for Experiment 1. Error bars represent the within subject standard error for the spacing effect.

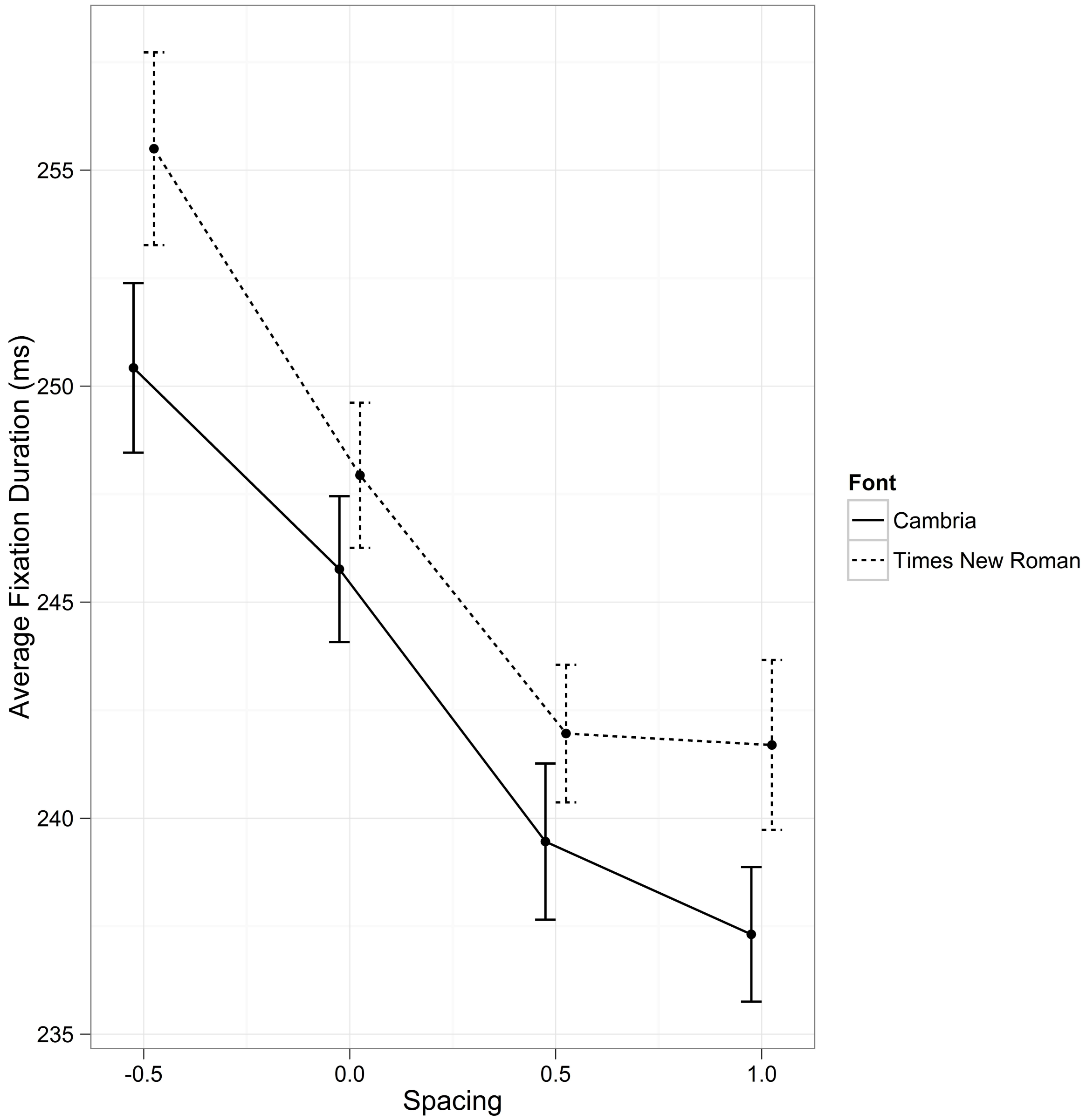

Figure 4. Average number of fixations for Experiment 1. Error bars represent the within subject standard error for the spacing effect.

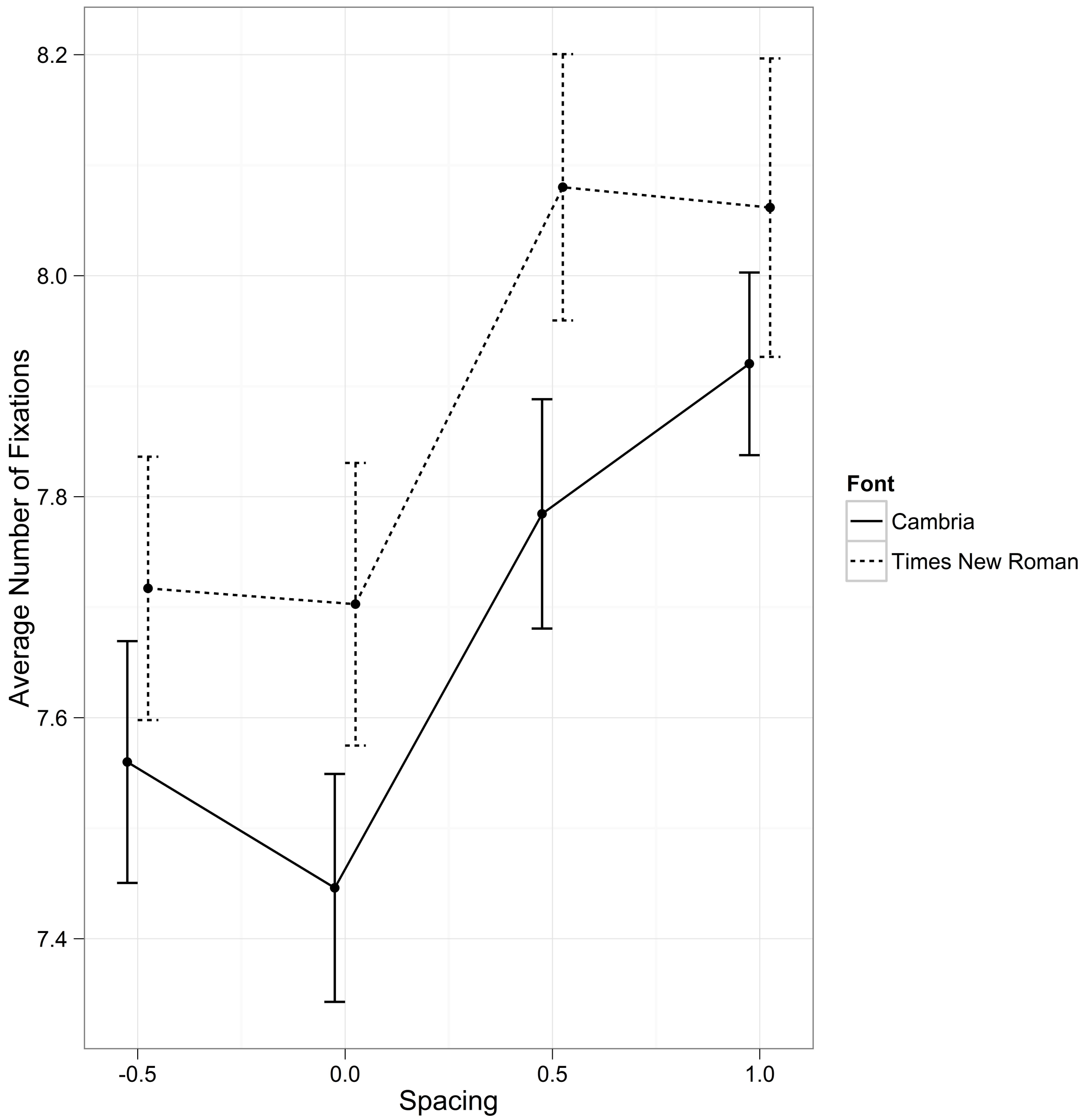

Figure 5. Critical saccade length distributions Experiment 1. Created with R's qplot density function.

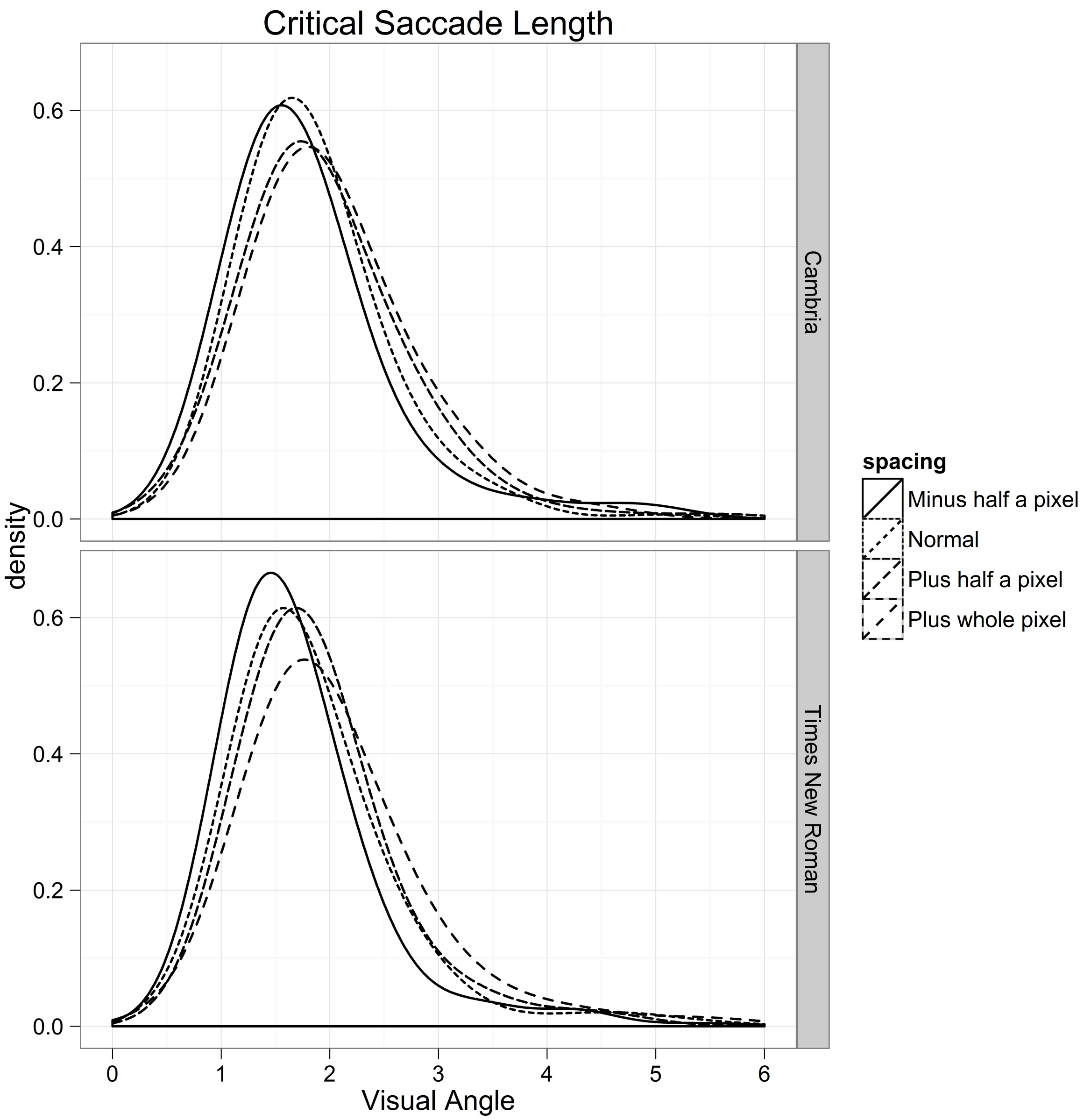

Figure 6. Example stimuli Experiment 2 with the Georgia sentences appearing above the Consolas ones. The Horizontal lines represent the regions used for fixation-based analyses. The top sentence of each pair is shown with adjusted spacing (decreased intra-word/increased inter-word). The bottom sentence of each pair is shown with normal spacing.

Figure 7. Fonts used in Experiment 1 and 2 all shown in 14 pt for comparison. From top to bottom: Times New Roman, Cambria, Georgia, Consolas.

Figure 8. Critical saccade length distributions Experiment 2. Created with R's qplot density function.