Effects of increased letter spacing on word identification and eye guidance during reading

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Abstract

The effect on eye movements during reading of increasing the space between letters in words was investigated under various word spacing conditions. Participants read sentences that included a high or low frequency target word, letters were displayed normally or with an additional space between adjacent letters, and one, two, or three spaces were present between each word. The spacing manipulations were found to modulate the effect of word frequency on the number and duration of fixations on target words, indicating more specifically that letter spacing affected actual word identification under various word spacing conditions. In addition, whereas initial fixations landed at the preferred viewing position (i.e., to the left of a word's center) for sentences presented normally, landing positions were nearer the beginnings of words when letter spacing was increased, and even nearer the beginnings of words when word boundary information was lacking. Findings are discussed in terms of the influence of textual spacing on eye movement control.

Key words: Eye movements in reading; word frequency effect; unspaced text; text spacing; letter spacing; word spacing.

Over recent years there has been renewed interest in the influence of text spacing on eye movements during reading (see Rayner, 1998, 2009, for a general review of this and other issues in eye movement research). Indeed, research on this topic has made a major contribution to understanding how the visual appearance of text influences reading behavior and has informed the development of models of eye movement control (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005; Reichle, Pollatsek, Fischer, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003).

Much of this research has focused on effects of manipulating spaces between words in text and, although it has sometimes been claimed that inter-word spaces might not be particularly important for reading (Epelboim, Booth, & Steinman, 1994, 1996; Epelboim, Booth, Ashkenazy, Taleghani, & Steinman, 1997; but see Rayner & Pollatsek, 1996; Rayner, Fischer, & Pollatsek,1998), research has consistently shown that removing spaces between words in English impairs reading performance (e.g., Fisher, 1976; Malt & Seamon, 1978; Morris, Rayner, & Pollatsek, 1990; Pollatsek & Rayner, 1982; Rayner et al., 1998; Spragins, Lefton, & Fisher, 1976). For example, Spragins et al. found that reading rates decreased by an average of 48% when inter-word spaces were removed, and similar decrements have been observed in research that replaced inter-word spaces with letters, digits, or blob-like gratings (Pollatsek & Rayner, 1982; Morris et al., 1990). Such evidence led Rayner, Pollatsek, and their colleagues (Morris et al., 1990; Pollatsek & Rayner, 1982; Rayner, et al., 1998) to propose that spaces between words in text are of considerable importance in reading English, and that inter-word spaces may help readers by aiding processes involved in word identification and eye guidance. In particular, Rayner et al. argued that inter-word spaces aid word identification by visually demarcating word boundaries, and that spaces between words to the right of a fixated word provide valuable information about word length and word boundaries that help guide where to fixate next, and so aid the progress of the eyes through text [1].

Particularly clear support for this account was provided by a study in which participants read spaced and unspaced texts in English that included one of a pair of target words that were matched for length but which differed in frequency (Rayner et al., 1998). It is well established that the duration of readers' fixations on words is sensitive to word frequency, indicating lexical access for word identification, and that words that occur often in written language receive shorter fixations than words that occur less frequently (e.g., Inhoff & Rayner, 1986; Juhasz, Liversedge, White, & Rayner, 2006; Juhasz & Rayner, 2003; Rayner & Duffy, 1986; Rayner, Sereno, & Rayney, 1996). Therefore, Rayner et al. argued that if removing the spaces between words increased the size of the word frequency effect, by making lower frequency words disproportionately harder to identify, this would show that the removal of inter-word spacing interfered with word identification rather than interfering with only a more superficial level of visual processing. As in previous research, Rayner et al. found that overall reading rates were slower for unspaced text (in this case 40-50% slower). However, gaze durations for target words showed a substantially larger word frequency effect when text was unspaced, indicating that the absence of inter-word spaces interfered with actual word identification.

Rayner et al. (1998) also found that participants fixated near the beginning of target words on their first fixation when inter-word spaces were absent. Research using normally-spaced text has shown that readers tend to fixate words just to the left of their center (i.e., at the *preferred viewing position*, Rayner, 1979). Therefore, the lesser likelihood of fixating this location when text was unspaced indicated that lack of space information interfered with normal eye guidance in reading. Finally, Rayner et al. included a condition in which three blank character spaces were inserted between words and observed a small benefit (in gaze durations for target words) for this more widely spaced text than for text presented normally. A similar effect was observed by Drieghe, Brysbaert, and Desmet (2005), who suggested that wider inter-word spacing facilitates reading by reducing lateral interference between adjacent words. However, Kolers, Duchnicky, and Ferguson (1981) observed no effects of doubling the spacing between words on individual fixations and reported only that readers made slightly fewer fixations when spacing between words was doubled.

While previous eye movement research has focused on the function of *word* spacing, much less is known in this area about the effects on word identification and eye guidance of increasing the spacing between *letters* in words. For example, it has been known for some time that when letters are more widely spaced, the reduction in lateral interference (also known as “visual crowding”) produced between adjacent letters improves letter identification (Bouma, 1970, 1973; Cavanagh, 2001; Chung, Levi, & Legge, 2001; Townsend, Taylor, & Brown, 1971). However, this improvement does not appear to benefit word perception, and other research has shown that increasing letter spacing beyond normal actually slows reading speed (Arditi, Knoblauch, & Grunwald, 1990; Chung, 2002; Legge, Rubin, Pelli, & Schleske, 1985; Van Overschelde & Healy, 2005; Yu, Cheung, Legge, & Chung, 2007). For example, Van Overschelde and Healy (2005) found that reading times for text were slower when letter spacing was greater than normal and argued that this slowdown was due to abnormal letter spacing disrupting the physical integrity of words, making it more difficult to integrate individual letters so that words could be identified using familiar visual configurations or units (e.g., Van Overschelde & Healy, 2005; see also e.g., Healy, 1976, 1994). However, while a slowdown in reading time suggests that word identification was impaired by letter spacing, it remains to be seen how patterns of eye movement behavior are affected and how they may contribute to this effect. Other research has provided insight into effects of abnormal letter spacing on eye movement behavior (e.g., Heller & Heinisch, 1985; O’Regan, Lévy-Schoen, & Jacobs, 1983), but has not been informative about the effects of these manipulations on processes involved in actual word identification. For example, O’Regan et al. found that increased letter spacing produced an increase in saccade lengths but their study provided no measure of any influence on word identification. Consequently, a major motivation for the present research was to employ a paradigm that combined word identification and eye movement behavior to gain a greater understanding of the influence of letter spacing during reading.

Accordingly, following the approach by Rayner et al. (1998), we assessed the effects of increased letter spacing on word identification and eye guidance by examining the influence of this variable on the effect of word frequency on fixation times for target words, and on landing positions on these words during naturalistic reading. Letter spacing was increased by one space and, to get a clearer picture of the influence of this increase, this letter spacing manipulation was combined with changes in word spacing. Sentences were displayed either normally (normal letter spacing/single word spacing), or letter spacing was increased by adding one character space between each letter in various word spacing conditions (see Figure 1): increased letter spacing/single word spacing (letter spacing was greater than normal and word spacing was normal); increased letter spacing/double word spacing (letter spacing was greater than normal and word spacing was twice that of normal); increased letter spacing/treble word spacing (letter spacing was greater than normal and word spacing was three times that of normal). Like Rayner et al., we used target words that were matched for length but which differed in written frequency, and these words were presented within sentence frames, as illustrated by the example sentences in Figure 1. The same stimuli had been used by Juhasz et al. (2006) to assess effects of word frequency on word identification and showed robust word frequency effects in that study.

----------------------Figure 1 about here----------------------

In line with the logic of Rayner et al. (1998), and following the findings of Healy, (1976, 1994; see also Healy & Cunningham, 2004) and Van Overschelde and Healy (2005), if increased letter spacing impairs word identification, processing of lower frequency target words should be disproportionately impaired by this manipulation and so a larger word frequency effect should occur in fixation times on target words when letter spacing is increased beyond normal. Word frequency effects should also reveal whether changes in word spacing modulate this influence. In particular, if (as seems likely) having just one word space when letter spacing is increased removes a normally clear visual cue to word boundaries which impairs word recognition then, in line with Rayner et al.'s findings, word frequency effects for target words should be largest in the increased letter spacing/single word spacing condition. However, if increasing word spacing beyond normal by an extra character helps offset this disruption by demarcating word boundaries, word frequency effects should be smaller in the increased letter spacing/double word spacing condition than in the increased letter spacing/single word spacing condition, and smaller still in the increased letter spacing/treble word spacing condition.

While an increase in letter spacing beyond normal might disrupt word identification because it disrupts the physical integrity of words (Healy, 1976, 1994; Healy & Cunningham, 2004; Van Overschelde & Healy, 2005), this pattern of effects might also occur because words are less visible when letter spacing is increased beyond normal. In particular, words within greater than normal letter spacing occupy a physical space that is unusually long and so will extend further away than normal from fixation. Consequently, because retinal acuity drops-off with increasing distance from the center of the fovea (e.g., Hilz & Cavonius, 1974; Østerberg, 1935), parts of these words will project to retinal regions that are of lower acuity than usual and this reduction in acuity for parts of words may lead to slower word identification. In addition, there is considerable evidence that readers extract information about words in the right parafovea and use this information to guide where to fixate next and to partially process a word before bringing it into foveal vision (Morris et al., 1990; O'Regan, 1979, 1980; Pollatsek & Rayner, 1982; Rayner, 1979; Rayner & Morris, 1992; Rayner et al., 1996). Therefore, when words occupy a physical space that is unusually long, parafoveal information may provide impoverished information about words to the right of fixation and, as a result, both eye guidance and parafoveal word processing may suffer.

The effects of spacing on eye guidance were assessed more specifically by examining the initial landing positions of fixations on target words. If letter spacing interferes with eye guidance, increased letter spacing should impair the targeting of saccades and, consequently, initial landing positions may deviate from the preferred viewing position (e.g., Rayner, 1979) observed when spacing is normal. For example, in line with Rayner et al.'s (1998) findings with text without word spaces, initial landing positions may be nearer the beginning of target words in the increased letter spacing/single word spacing condition than for text presented with normal letter and word spacing, due to the absence of a clear visual cue to word boundaries and the cautious use of textual content to provide information about word boundaries. Moreover, if increased letter spacing impairs the integrity of word extent, targeting the preferred viewing position may be difficult even when word spaces provide some demarcation of word boundaries (as in the increased letter spacing/double word spacing and increased letter spacing/treble word spacing conditions) and first fixations may fall closer to the beginnings of words in these conditions, relative to text that is normally spaced.

Method

Participants. Sixteen native English speakers from the University of Leicester participated for course credit.

Stimuli and Design. Stimuli consisted of 80 sentences (as used by Juhasz et al., 2006). Each sentence appeared in one of four conditions (see Figure 1): normal letter spacing/single word spacing; increased letter spacing/single word spacing; increased letter spacing/double word spacing; increased letter spacing/treble word spacing.

Target words comprised 40 high frequency nouns (mean 143 counts per million according to the CELEX database; Baayen, Piepenbrock, & Gulikers, 1995) and 40 low frequency nouns (mean 1.35 counts per million). These 80 words were arranged into 40 pairs of high and low frequency words matched for length (mean = 7.85 characters, range = 7-10 characters) and were shown to each participant in one of 40 pairs of neutral sentence frames that had been constructed so that each member of a target word pair plausibly fitted each pair of sentence frames and the predictability of each word within each pair of sentence frames was matched (see Juhasz et al., 2006). Each complete sentence was 49 to 60 characters long (an example sentence and target words is shown in Figure 1). Each participant saw each sentence frame and target word only once and the presentation of target words in sentence frames was counterbalanced across participants. In addition, the presentation of sentences in each spacing condition was counterbalanced across participants so that each participant saw 20 sentences in each spacing condition, and saw equal numbers of high and low frequency target words in each spacing condition. Thus, there were two within-participants independent variables: spacing condition and target word frequency. An additional 68 sentences served as filler items. Half of the filler items were presented with normal spacing and the others were presented with increased word spacing (and normal letter spacing). Stimuli (and filler trials) were presented in a pseudo-random order. The experiment began with 6 practice trials to give readers some familiarity with reading under abnormal spacing conditions.

Apparatus. A Fourward Technologies Dual Purkinje Generation 6 Eye-tracker recorded participants' right eye movements during stimulus viewing. The eye-tracker has an angular resolution of 10 min of arc and was interfaced with a PC that sampled fixation position every millisecond. Sentences were presented as white text on a black background in Courier font on a 17 inch display monitor. Sentences always started in the same location in the upper left quadrant of the screen. Target words were always located close to the middle of a sentence and thus appeared near the center of the screen. At the 80 cm viewing distance used in the study, three characters subtended approximately 1 degree of visual angle.

Procedure. Before the start of the experiment, participants received an explanation of the procedure, and were forewarned that the text might be difficult to read and that even on those trials they should attempt to read normally and for comprehension. Participants were seated at the eye-tracker and a bite-bar was used to prevent head movements, and the calibration procedure was completed. Before the start of each trial, a fixation box the same size as one alphabetic character appeared in the upper left quadrant of the screen. When participants fixated this box, the experimenter initiated the presentation of a sentence, with the first character of the sentence replacing the fixation box. The eye-tracker was re-calibrated if participants' fixations did not match the fixation box. Participants took breaks as required. Twenty-five percent of trials were followed by a two-alternative forced choice question testing comprehension of sentence content (these were the same comprehension questions as used by Juhasz et al., 2006) which participants answered by pressing the button corresponding to the correct answer on a button box. As in the Juhasz et al. study, comprehension was above 90% for each participant.

Results

An automatic procedure incorporated fixations of less than 80 ms into larger fixations within one character and deleted fixations less than 40 ms not within three characters of another fixation. Fixations over 1200 ms were truncated. Trials on which sentences were not read fully or that had tracker loss were deleted. This accounted for only 4% of trials.

Global eye movement measures. Effects of spacing on global eye movement measures were assessed by examining the influence of spacing condition on average fixation durations, words-per-minute reading rates, the number of progressive and regressive fixations, and the mean length (in character spaces) of progressive and regressive saccades. Data for each of these measures were analysed by performing one-way analyses of variance (ANOVA), computing error variance over participants (F_1) and sentences (F_2). Mean global eye movement data are shown in Table 1.

----------------------Table 1 about here--------------------

There was a significant effect of spacing condition on both average fixation durations, $F_1(3,45) = 40.32$, $p<.001$, $F_2(3,117) = 42.59$, $p<.001$, and reading rates, $F_1(3,45) = 77.79$, $p<.001$, $F_2(3,117) = 59.69$, $p<.001$. Tukey tests revealed that the effects were due to longer average fixation durations and slower reading rates in the increased letter spacing/single word spacing condition compared to all other conditions ($p<.05$), which did not differ significantly from each other (ps>.05). Thus, sentences were read less efficiently when clear visual cues to word boundaries were lacking.

Spacing also had an effect on the number of progressive, $F_1(3,45) = 135.85$, $p<.001$, $F_2(3,117) = 267.99$, $p<.001$, and regressive, $F_1(3,45) = 59.34$, $p<.001$, $F_2(3,117) = 61.45$, $p<.001$, fixations. Tukey tests revealed fewest progressive fixations in the normal letter spacing/single word spacing condition, more in the increased letter spacing/double word spacing and increased letter spacing/treble word spacing conditions, and most in the increased letter spacing/single word spacing condition (ps<.001). In addition, more regressive fixations were made in the increased letter spacing/single word spacing condition than in all other conditions (ps<.01), which did not differ from each other (ps>.5). Thus, more progressive fixations were required when letter spacing was increased beyond normal, and this influence was modulated by word spacing. However, the number of regressive fixations was unaffected by letter spacing unless word spacing removed normally clear cues to word boundaries.

Effects of spacing were also observed in the length of progressive, $F_1(3,45) = 163.41$, $p<.001$, $F_2(3,117) = 301.70$, $p<.001$, and regressive, $F_1(3,45) = 9.59$, $p<.001$, $F_2(3,117) = 18.14$, $p<.001$ saccades. Tukey tests showed that progressive saccades were shortest in the increased letter spacing/single word spacing condition, longer in the normal letter spacing/single word spacing condition, longer still in the increased letter spacing/double word spacing condition, and longest of all in the increased letter spacing/treble word spacing condition (*p*s<.001). In addition, regressive saccades were shorter in the increased letter spacing/single word spacing condition than in all other conditions (*p*s<.01). No other differences were significant ($p>.5$). Thus, not only did the absence of clear visual cues to word boundaries in the increased letter spacing/single word spacing condition produce more progressive and regressive fixations but both types of saccades were shorter in this condition than in all other conditions, indicating that participants had considerable difficulty in reading text when word boundary information was lacking. In addition, progressive saccades were longer when letter spacing was increased beyond normal and word spacing was sufficient to provide clear cues to word boundaries, indicating that the programming of progressive saccades can accommodate changes in letter spacing when word spacing allows.

Target word eye movement measures. The effect of spacing on word identification and eye guidance was assessed by examining standard eye movement measures (see Rayner, 1998, 2009) for high and low frequency target words. This involved conducting 4 (spacing condition) x 2 (target word frequency) ANOVAs, computing error variance over participants (F_1) and stimuli (F_2), for first fixation durations (duration of the first fixation on a word), single fixation durations (duration of fixation on words receiving only one first-pass fixation), gaze durations (sum of all fixations on a word before a saccade from it), number of first-pass fixations, probability of a first-pass regression, and total reading times (sum of all fixations) for target words. Mean data for target words are shown in Table 2.

---------------------Table 2 about here-------------------

First fixation durations. First fixation durations for target words revealed a main effect of spacing condition, $F_1(3,45) = 14.60$, $p<.001$, $F_2(3,234) = 15.83$, $p<.001$. Tukey tests showed that first fixation durations were longer for targets in the increased letter spacing/single word spacing condition than in all other conditions (ps<.01), which did not differ from each other ($p>.10$). There was also a main effect of target word frequency, $F_1(1,15) = 16.29$, $p<.01$, $F_2(1,78) = 6.55$, $p<.05$, due to shorter fixation durations for higher frequency words (17 ms effect). However, spacing condition did not modulate the size of the word frequency effect, Fs<1.

Single fixation durations. Very few single fixations occurred for target words (55%), especially when letter and word spacing was increased beyond normal. Indeed, an analysis computing error variance over stimuli (F_2) was impossible and an analysis computing error variance over participants (F_1) could be performed for only 13 of the 16 participants. Nevertheless, the pattern of means for these participants, and the pattern of results from the ANOVA, resembled those obtained for first fixation durations. Namely, there was a main effect of spacing condition, $F_1(3,36) = 3.19$, $p<.05$, and Tukey tests showed that fixation durations were longer for targets in the increased letter spacing/single word spacing condition than in the normal letter spacing/single word spacing condition ($p<.05$), and no other differences were significant ($p>.10$). In addition, there was a main effect of target word frequency, $F_1(1,12) = 6.38$, $p<.05$, due to shorter fixation durations for higher frequency words (20 ms effect). However, spacing condition did not modulate the size of the word frequency effect, $F_1<1$.

Gaze durations. Gaze durations for target words revealed main effects of spacing condition, $F_1(3,45) = 101.10$, $p<.001$, $F_2(3,234) = 131.34$, $p<.001$, word frequency, $F_1(1,15) = 43.85$, $p<.001$, $F_2(1,78) = 31.09$, $p<.001$, and an interaction between these factors, $F_1(3,45) = 6.03$, $p<.01$, $F_2(3,234) = 5.68$, $p<.01$. Tukey tests showed that gaze durations were shortest for targets in the normal letter spacing/single word spacing condition, longer in the increased letter spacing/treble word spacing condition, longer still in the increased letter spacing/double word spacing condition, and longest of all in the increased letter spacing/single word spacing condition (ps≤.05). Further analyses showed that the word frequency effect was smallest in the normal letter spacing/single word spacing condition (50 ms effect), larger in the increased letter spacing/treble word spacing condition (89 ms effect), larger still in the increased letter spacing/double word spacing condition (129 ms effect), and largest of all in the increased letter spacing/single word spacing condition (229 ms effect; all *p*s<.05).

These findings for word frequency revealed an effect of letter spacing on target word identification that was modulated by spacing between words. As expected, the frequency effect was largest in the increased letter spacing/single word spacing condition, indicating, in line with findings reported by Rayner et al. (1998), that an absence of clear visual cues to word boundaries caused disruption to word identification. Increasing word spacing by one extra character space in the increased letter spacing/double word spacing condition helped offset (but not eliminate) this disruption and the frequency effect was further diminished (but still greater than for text presented normally) when word spacing was increased further in the increased letter spacing/treble word spacing condition, indicating that wider word spacing aided word identification when letter spacing was increased beyond normal.

Number of first-pass fixations. An analysis of the number of first-pass fixations for target words revealed main effects of spacing condition, $F_1(3,45) = 80.75$, $p<.001$, $F_2(3,234) = 84.76$, $p<.001$, and target word frequency, $F_1(1,15) = 37.21$, $p<.001$, $F_2(1,78) = 24.65$, $p<.001$, and a significant interaction, $F_1(3,45) = 6.32$, $p<.01$, $F_2(3,234) = 3.84$, $p=.01$. Tukey tests showed that targets received fewest first pass fixations in the normal letter spacing/single word spacing condition, more first-pass fixations in increased letter spacing/treble word spacing and increased letter spacing/double word spacing conditions, and most first-pass fixations in the increased letter spacing/single word spacing condition (*p*s<.05). Even though the number of first-pass fixations did not differ for higher and lower frequency targets in normal letter spacing/single word spacing sentences, lower frequency targets attracted more first-pass fixations than higher frequency targets when letter spacing was increased beyond normal (all *p*s<.01), although this frequency effect was itself unaffected by word spacing (mean effects .60 for increased letter spacing/single word spacing sentences, .50 for increased letter spacing/double word spacing sentences, and .40 for increased letter spacing/treble word spacing sentences).

First-pass regressions. First-pass regressions from target words revealed a main effect of spacing condition, $F_1(3,45) = 9.19$, $p<.001$, $F_2(3,234) = 5.67$, $p<.01$, and no other significant effects (Fs<1.3). Tukey tests showed that there were more regressions from target words in normal letter spacing/single word spacing and increased letter spacing/single word spacing conditions than in the other conditions ($p<.05$), which did not differ from each other (ps>.90).

Total reading times. Total reading times revealed main effects of spacing condition, $F_1(3,45) = 51.97$, $p<.001$, $F_2(3,234) = 86.97$, $p<.001$, and target word frequency, $F_1(1,15) = 25.68$, $p<.001$, $F_2(1,78) = 26.79$, $p<.001$, and a significant interaction, $F_1(3,45) = 9.10$, $p<.01$, $F_2(3,234) = 7.18$, $p<.001$. Tukey tests showed that total reading times were shortest for targets in the normal letter spacing/single word spacing condition, longer in the increased letter spacing/treble word spacing condition, longer still in the increased letter spacing/double word spacing condition, and longest of all in the increased letter spacing/single word spacing condition (ps<.01). Further analyses showed that the word frequency effect was smallest in the normal letter spacing/single word spacing condition (87 ms effect), longer in the increased letter spacing/treble word spacing and increased letter spacing/double word spacing conditions (121 ms and 152 ms effects, respectively), and longest of all in the increased letter spacing/single word spacing condition (513 ms effect; ps<.05). Thus, as with gaze durations, the word frequency effect in total reading times for target words revealed an effect of letter spacing that was modulated by word spacing. As with gaze durations, this word frequency effect was largest in the increased letter spacing/single word spacing condition, indicating that a lack of clear visual cues to word boundaries caused substantial disruption to word identification. Increasing word spacing by one extra character space in the increased letter spacing/double word spacing condition helped offset this disruption. However, although there was a numerical trend in this direction, further increases in word spacing in the increased letter spacing/treble word spacing condition did not benefit word identification significantly.[2]

Initial landing position. Although the same target words were used in each spacing condition, words with increased letter spacing were physically longer than words presented normally. Therefore, initial landing positions for target words were computed in terms of the proportional distance into a word from its left boundary at which the first fixation was made. Table 3 shows the mean proportional distance into a word of the initial landing positions for target words in each spacing condition.

----------------------Table 3 about here--------------------

Initial landing positions for target words differed significantly across spacing conditions, $F_1(3,45) = 27.98$, $p<.001$, $F_2(3,234) = 30.30$, $p<.001$, but were unaffected by target word frequency or an interaction of these factors, *F*s<1.4. For words in the normal letter spacing/single word spacing condition, initial landing positions were a mean of 39% in from the left boundary of words. This replicates the standard finding that the preferred viewing position for words is a little to the left of a word's center (e.g., Rayner, 1979). Tukey tests revealed that initial landing positions were further to the left of this location in increased letter spacing/treble word spacing and increased letter spacing/double word spacing conditions (i.e., first fixations landed a mean of 31% and 33%, respectively, in from the left boundary, *p*s<.05), and even further to the left in the increased letter spacing/single word spacing condition (i.e., first fixations landed a mean of only 23% in from the left boundary, *ps*<.05). Thus, initial landing positions were nearer the beginning of words than normal when letter spacing was increased beyond normal, and this effect was exacerbated when clear visual cues to word boundaries were lacking.

Discussion

The results of this experiment were clear and reveal that the spacing between letters in words influences both word identification and eye guidance during reading and that this influence is modulated by inter-word spacing. An assessment of global eye movement measures showed that general eye movement parameters were particularly affected in the increased letter spacing/single word spacing condition, where readers made more and longer fixations than normal, separated by progressive and regressive saccades that were shorter than in the normal spacing condition, indicating that participants had considerable difficulty reading text when clear visual cues to word boundaries were lacking. Effects in other conditions showed also that participants made more progressive fixations and longer progressive saccades than normal (with no effects for regressive eye movements) to accommodate text that occupied a physical space that was unusually long when letter spacing was increased beyond normal and word spacing was sufficient to provide clear cues to word boundaries. These effects indicate that the programming of progressive saccades can adjust to increases in letter spacing when word spacing allows. Moreover, the finding that effects of spacing were obtained in general eye movements parameters demonstrates clearly that eye movements are sensitive to the influence of letter spacing under different word spacing conditions.

Following Rayner et al. (1998), we assessed the influence of spacing on word identification and eye guidance by examining the influence of our manipulation on the word frequency effect in fixation times for target words, and on landing positions in these words. Although spacing modulated word frequency effects in several measures (including the number of first-pass fixations and total reading times for target words), its influence was seen most clearly in gaze durations for target words, which showed robust word frequency effects. These revealed an influence of letter spacing on word identification that was modulated by word spacing, such that word frequency effects were largest for target words in sentences with increased letter spacing and only one inter-word space, smaller when word spacing was increased to two character spaces, smaller still when word spacing was increased to three character spaces, and smallest of all in sentences with normal letter and word spacing. Thus, although three blank character spaces between words with increased letter spacing was sufficient to provide visual cues to word boundaries, these findings indicate that readers nevertheless had difficulty when the space between letters was greater than normal.[3] As these effects emerged in an eye movement measure (i.e., gaze duration) that is sensitive to early stages of word identification (e.g., Rayner & Duffy, 1986; Rayner et al., 1998; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989), it appears that our manipulation of spacing affected processes associated with target word identification.

The word frequency effect for targets in sentences with normal spacing was similar in size to that reported by Juhasz et al. (2006; i.e., a 50 msec effect in the present experiment compared to a 41 msec effect in the Juhasz et al. study). Therefore, it seems that the sentences we used had the capacity to inspire normal reading behavior observed in previous research. Moreover, the fact that the word frequency effect was substantially larger when letter spacing was greater than normal (even when word spacing provided clear cues to word boundaries) indicates that an increase in letter spacing beyond normal does indeed disrupt the word identification process. Previous research (e.g., Arditi et al., 1990; Chung, 2002; Legge et al., 1985; Van Overschelde & Healy, 2005) had shown that abnormal letter spacing slows reading rates, but our findings reveal more directly (by using eye movement measures for high and low frequency words) that increasing letter spacing disrupts processes involved in actual word identification.

Van Overschelde and Healy (2005) attributed the slowdown in reading rates they observed with abnormal letter spacing to disruption of the physical integrity of words (see also Healy, 1976, 1994; Healy & Cunningham, 2004), and the present results suggest that this disruption interferes with the actual identification of words during reading. Moreover, by revealing that eye movements are sensitive to this influence, our findings add further support to the claim that cognitive processes involved in word identification have an on-line influence on eye movements in reading (e.g., Rayner & Duffy, 1986; Rayner et al., 1996; see also Reichle et al., 2003) by demonstrating that decisions about when to move the eyes are affected by the lexical processing of words. Increased letter spacing may make it more difficult to integrate individual letters so that words can be identified using familiar visual configurations or units (e.g., Van Overschelde & Healy, 2005; see also e.g., Healy, 1976, 1994; Healy & Cunningham, 2004). However, disruption to the physical integrity of words produced by increased letter spacing might also interfere with word identification in a number of other ways. For example, an increase in letter spacing distorts word length and this, in turn, may disrupt word identification (for a discussion of this phenomenon, see, e.g., Jordan, 1990, 1995). In addition, as words with increased letter spacing occupy a larger than normal physical space, parts of words will project to retinal regions that are of lower visual acuity than usual, and this too may impair word identification (O'Regan et al., 1983). Moreover, when words occupy a physical space that is unusually long, parafoveal information may provide impoverished information about words to the right of fixation which disrupts the targeting of progressive saccades and impedes the parafoveal pre-processing of words. As a consequence, readers may be more likely to re-fixate target words with increased letter spacing to correct for landing position errors, and so give rise to increased first-pass fixations, which were observed in the present experiment. Moreover, readers may fixate words for longer to compensate for the loss of parafoveal information, and therefore produce inflated first fixation durations or gaze durations on words, which was also observed in the present experiment. Finally, if, as seems likely, impoverished parafoveal preview information impacts on the processing of lower frequency words to a greater extent (because lower frequency words in the parafovea require more processing to be identified; e.g., Rayner et al., 1996; Rayner & Well, 1996), this may explain the larger word frequency effect in gaze durations observed in conditions with increased letter spacing than for text presented normally.

We turn now to the modulating effects of word spacing. Consistent with previous research into effects of eliminating spaces between words (Rayner et al., 1998), word identification was disrupted most when word spacing did not clearly delimit word boundaries. Increasing word spacing to two character spaces reduced the size of the word frequency effect, suggesting that clear visual cues to word boundaries improved actual word identification. However, increasing word spacing from two character spaces to three reduced the size of the word frequency effect even further. Thus, it seems that further enlarging the space between words (beyond that required to effectively delimit word boundaries) in sentences which have increased letter spacing can benefit word identification by increasing further the salience of word boundaries. What appears important here is the ratio of word to letter spacing, which, when lowest (in the increased letter spacing/single word spacing condition), produced the largest word frequency effect. Increasing this ratio, by the addition of an extra space between words in the increased letter spacing/double word spacing condition produced a smaller word frequency effect, and this effect was smaller still when the ratio was improved further in the increased letter spacing/treble word spacing condition. This aspect of our findings resonates with other research showing facilitatory effects on eye movements of increasing the space between words presented normally beyond that required to delimit word boundaries (Drieghe et al., 2005; Rayner et al., 1998). However, whereas this previous research has shown that increasing word spacing can facilitate reading, the word frequency effects we observed clarify these effects by indicating that manipulating the ratio of word to letter spacing in a sentence may influence processes involved in word identification. Thus, while increased word spacing may reduce lateral inhibition from adjacent words (Drieghe et al., 2005), it seems that effects of word spacing go beyond this relatively early visual influence and affect access to lexical representations.

Although gaze durations showed clear effects of spacing on processes associated with target word identification, these effects were not so clear in first fixation durations, which showed standard (and highly robust) word frequency effects but no interaction between spacing condition and word frequency. In this respect, the data were similar to those obtained by Rayner et al. (1998) for unspaced text with normal letter spacing, which also did not reveal a reliable influence of word spacing on the word frequency effect in first fixation durations, but did reveal an effect in gaze durations. Our data also showed that readers made more first-pass fixations on target words, especially for lower frequency words, when letter spacing was increased (irrespective of word spacing). Thus, it appears that effects of spacing on word processing emerged in gaze durations for target words and were due to readers being more likely to re-fixate words when reading sentences with greater than normal letter spacing under different word spacing conditions.

Total reading times showed a pattern of effects similar to that observed for gaze durations, although the word frequency effect in total reading times for target words in the increased letter spacing/single word spacing condition was substantially larger than in the other conditions, and so showed that readers had particular difficulty in identifying words when word boundary information was lacking. The findings for first-pass regressions were of greater interest, however, and suggested that increased letter spacing interfered with eye guidance by impairing the programming of regressive saccades. These findings showed that there were fewer regressions from target words when letter spacing was increased beyond normal and word spacing was also greater than normal (i.e., increased letter spacing/double word spacing and increased letter spacing/treble word spacing) compared to text presented with normal letter and word spacing. It is likely that this effect was due to the longer physical length of target words when letter spacing was increased beyond normal and word spacing was also greater than normal. Targets with increased letter spacing were almost twice as long as the same words presented normally, and these words were also spaced further apart than normal, in increased letter spacing/double word spacing and increased letter spacing/treble word spacing conditions. Consequently, when readers fixated a target word with increased letter spacing that also had wider than normal word spacing, information about words to the left (or right) of this word will have projected further into the parafovea than usual and so been less visible. This reduced visibility of parafoveal information appears to have interfered with the programming of regressive saccades, and so reduced the likelihood of a regression. The same effect was not observed in the increased letter spacing/single word spacing condition, where the lack of visual information about word boundaries in this condition inspired a higher frequency of regressive saccades (see also Rayner et al., 1998; and see Mitchell, Shen, Green, & Hodgson, 2008, for evidence of linguistic and non-linguistic influences on regression control).

Finally, consider the landing position data. These showed that when sentences were presented with normal letter and word spacing, first fixations landed just to the left of the centre of target words (i.e., 39% from the left boundary of these words). This replicated the standard finding that words have a preferred viewing position located a little to the left of each target word’s center (e.g., Rayner, 1979), and therefore provided further evidence that the sentences we used had the capacity to inspire normal reading behavior. However, when letter spacing was increased beyond normal, in increased letter spacing/double word spacing and increased letter spacing/treble word spacing conditions, fixations landed further to the left of center (i.e., mean 32% from the left boundary of words) and even further to the left in the increased letter spacing/single word spacing condition (i.e., only 23% from the left boundary), and therefore nearer the beginning of target words. These deviations from the preferred viewing position showed that abnormal letter spacing disrupted eye guidance, and that most disruption occurred when clear information about word boundaries was lacking. As noted already, lack of visual information about word boundaries also produced substantially more first-pass fixations on target words. Therefore, it seems that when spacing degrades information about word length and word boundaries, readers have considerable difficulty in saccade planning and may adopt a strategy that involves moving the point of fixation cautiously along a line of text until textual content provides information about word boundaries and identities. Rayner et al. (1998) also found that readers fixated much nearer the beginning of words, and made shorter saccades, when text lacked word spaces, and such findings are consistent with difficulty in saccade planning causing readers to adopt a more cautious reading strategy when word boundary information is lacking.

The observed tendency to undershoot the preferred landing position (measured by target word landing position) also occurred, to a lesser extent, for increased letter spacing/double word spacing and increased letter spacing/treble word spacing sentences. However, the increased salience of word boundaries in these conditions (due to increased word spacing) suggests that this disruption is less likely to be due to a lack of word boundary information and disruption to eye guidance in these sentences is likely to be due to wider than normal letter spacing. This effect may be related to the finding that landing positions fall further to the left in longer words (called the *saccadic range error*), because saccades tend to undershoot targets and this tendency is greater for longer saccades (e.g., McConkie, Kerr, Reddix, & Zola, 1998). In the present case, adding spaces between letters in words served to increase the overall physical extent of words and so would increase the length of the saccade needed to fixate the preferred viewing position in a word, with the consequence that fixations were more likely to undershoot this location.

In addition to increasing the physical length of a word, increased letter spacing will also disrupt the normal spatial frequency content of words (e.g., Legge et al., 1985; Patching & Jordan, 2005a, 2005b) and this too may contribute to making words more difficult to process. There is a growing body of research that indicates an important role in word recognition for different bands of spatial frequency information, from coarse scale (low frequency) information that describes the overall extent of a word to more fine scale (high frequency) information necessary to specify individual letters and features (Allen & Madden, 1990; Allen, Smith, Lien, Kaut & Canfield, 2009; Boden & Giaschi, 2000; Dakin & Morgan, 1999; Jordan, 1990, 1995; Jordan & Bevan, 1996; Jordan & de Bruijn, 1993; Leat & Munger, 1994; Legge et al., 1985; Patching & Jordan, 2005a, 2005b).The disruption to normal spatial frequency content caused by increased letter spacing may mean that coarse scale information corresponding to the overall extent of words is particularly distorted, making words in these conditions afford poor quality information about word extent and location, which may also interfere with saccadic programming. Further research is needed to determine the nature of the spatial frequency information that is afforded by words and the role it plays in facilitating eye guidance.

In sum, the present findings extend previous research into effects of spacing on eye movement control by revealing that increasing the spacing between letters in words beyond normal and manipulating the spacing between words in sentences affects fundamentally when and where the eyes move during reading. In particular, the results show clearly that increasing the space between letters in words beyond normal under various word-spacing conditions disrupts processes involved in identifying words and in guiding the eyes through text. Nevertheless, disruption caused by increased letter spacing was not catastrophic, so long as visible word boundary information was available, and this suggests that skilled readers, such as the participants in our study, are able to accommodate changes in letter spacing without serious disruption to reading.

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Footnote

1. Other research has shown that adding spaces to text in languages that are naturally unspaced can benefit the reading of Thai (Kohsom & Gobet, 1997; Winskel, Radach, & Luksaneeyanawin, 2009) and Japanese written in pure syllabic (i.e., Hiragana) script (Sainio, Hyöna, Bingushi, & Bertram, 2007). However, such benefits do not appear to be universal, and have not been observed for Chinese (Bai, Yan, Liversedge, Zang, & Rayner, 2008; Hsu & Huang, 2000a, 2000b; Inhoff, Liu, Wang, & Fu, 1997) or for Japanese written in a mixture of ideographic and syllabic characters (i.e., Kanji-Hiragana, Sainio et al., 2007).

2. In addition to these analyses, the possibility that practice effects influenced reading in the abnormal spacing conditions was assessed by computing reading time difference for target words in each abnormal spacing condition compared to text presented normally and correlating these values with trial order. The absence of a significant correlation in first fixation durations, gaze durations, or total reading times (all ps<.13) suggests that reading performance was unaffected by an increased exposure to abnormally spaced text over the course of the experiment.

3. It seems clear that the ratio of word to letter spacing in the increased letter spacing/treble word spacing is more favourable for reading than in the other increased letter spacing conditions, and appears to provide clear visual cues to word boundaries. Thus, the difficulty experienced even in this condition is likely to reflect difficulty in processing words with greater than normal letter spacing rather than difficulty in establishing the boundaries between words.

Figure Legend

Figure 1. Example stimulus showing manipulation of inter-letter and inter-word spacing for a sentence containing a high (e.g., service) and low (e.g., cuisine) frequency target word.

Table 1. Global eye movement measures (standard error in parentheses).

	Spacing			
	increased letter spacing/single word spacing	increased letter spacing/double word spacing	increased letter spacing/treble word spacing	normal letter spacing/single word spacing
Average fixation duration	296 (7.8)	259 (5.5)	253 (5.5)	260 (6.0)
Reading rate (words/minute)	207 (5.7)	238 (5.0)	242 (5.3)	235 (5.7)
No. of progressive fixations	24.4 (1.2)	15.6 (0.6)	15.7 (0.8)	13.1 (0.6)
No. of regressive fixations	5.8 (0.5)	2.8 (0.3)	2.8 (0.3)	2.8 (0.3)
Progressive saccade length (character spaces)	6.9 (0.2)	10.9 (0.4)	11.8 (0.4)	8.5 (0.4)
Regressive saccade length (character spaces)	4.9 (0.2)	6.8 (0.5)	7.4 (0.4)	8.2 (0.8)

Table 2. Mean eye movement data for high and low frequency target words (standard error in parentheses).

	Spacing							
	increased letter spacing/single word spacing		increased letter spacing/ double word spacing		increased letter spacing/treble word spacing		normal letter spacing/single word spacing	
	Target Word frequency							
	High	Low	High	Low	High	Low	High	Low
First fixation duration (msec)	277 (11.6)	294 (13.3)	239 (7.8)	251 (8.1)	235 (8.8)	249 (9.8)	229 (9.3)	252 (9.5)
	M = 285 (10.7)		*M* = 245 (6.8)		*M* = 242 (8.3)		*M* = 240 (8.6)	
Single fixation duration (msec)	319 (82.8)	368 (120.1)	264 (24.6)	298 (23.5)	265 (17.0)	267 (17.1)	233 (10.2)	262 (10.3)
	M = 343 (75.4)		*M* = 281 (23.4)		*M* = 266 (15.3)		*M* = 248 (8.6)	
Gaze duration (msec)	600 (36.5)	829 (56.0)	328 (17.8)	457 (35.3)	303 (20.6)	392 (34.1)	259 (12.5)	309 (14.6)
	M = 714 (39.4)		*M* = 392 (25.1)		*M* = 348 (24.3)		*M* = 284 (12.3)	
Number of first-pass fixations	2.2 (.10)	2.8 (.14)	1.4 (.06)	1.9 (.13)	1.3 (.09)	1.7 (.12)	1.2 (.03)	1.2 (.04)
	M = 2.5 (.11)		*M* = 1.7 (.08)		*M* = 1.5 (.09)		*M* = 1.2 (.03)	
First-pass regression (%)	23.6 (4.5)	27.2 (4.9)	11.6 (2.9)	13.5 (2.7)	14.8 (3.6)	10.6 (3.0)	19.0 (4.5)	25.8 (4.6)
	M = 25.4 (4.1)		*M* = 12.6 (2.0)		*M* = 12.7 (2.9)		*M* = 22.4 (3.9)	
Total reading time (msec)	848 (75.2)	1361 (158.7)	397 (23.2)	549 (36.7)	363 (25.4)	484 (35.6)	332 (20.4)	419 (35.5)
	M = 1107 (108.0)		*M* = 471 (25.8)		*M* = 416 (26.5)		*M* = 350 (22.3)	

Table 3. Landing position within word proportional to physical word length (standard error in parentheses).

	Spacing			
Target Word frequency	increased letter spacing/ single word spacing	increased letter spacing/double word spacing	increased letter spacing/treble word spacing	normal letter spacing/ single word spacing
High	.23 (.01)	.32 (.02)	.33 (.02)	.38 (.02)
Low	.23 (.02)	.34 (.02)	.29 (.02)	.39 (.02)
	M =.23 (.01)	*M* =.33 (.01)	*M* =.31 (.02)	*M* =.39 (.02)

Figure 1

Increased *letter spacing/single word spacing*

```
                        s e r v i c e
I e n j o y e d t h e g r e a t         a t t h e l o c a l T h a i r e s t a u r a n t .
                        c u i s i n e
```

Increased *letter spacing/double word spacing*

```
                                 s e r v i c e
I  e n j o y e d  t h e  g r e a t           a t  t h e  l o c a l  T h a i  r e s t a u r a n t .
                                 c u i s i n e
```

Increased *letter spacing/treble word spacing*

```
                                        s e r v i c e
I   e n j o y e d   t h e   g r e a t                 a t   t h e   l o c a l   T h a i   r e s t a u r a n t .
                                        c u i s i n e
```

Normal letter spacing/single word spacing

```
                   service
I enjoyed the great         at the local Thai restaurant.
                   cuisine
```