Abstract = 147 words

Word Count of Main Text = 5629 words

The effects of interword spacing on the eye movements of young and older readers

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Abstract

Recent evidence indicates that older adults (aged 65+) are more disrupted by removing interword spaces than young adults (aged 18-30). However, it is not known whether older readers also show greater sensitivity to the more subtle changes to this spacing that frequently occur during normal reading. In the present study the eye movements of young and older adults were examined while reading texts for which interword spacing was normal, condensed to half its normal size, or expanded to 1.5 times its normal size. Although these changes in interword spacing affected eye movement behaviour, this influence did not differ between young and older adults. Furthermore, a word frequency manipulation showed that these changes did not affect word identification for either group. The results indicate that older adults can adapt their eye moment behaviour to accommodate subtle changes in the spatial layout of text equally effectively as young adults.

Keywords: Eye movements, reading, older adults, interword spacing

Introduction

Older adults (aged 65+) typically read more slowly than young adults (aged 18-30) and produce eye movement patterns that are characterised by more and longer fixations, more regressions, longer progressive saccades, and more word skipping in comparison to young adults, although comprehension abilities appear intact (Kliegl, Grabner, Rolfs, & Engbert, 2004; Paterson, McGowan, & Jordan, 2013a; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Rayner, Castelhano, & Yang, 2009). These changes may reflect, at least to some extent, a general slowdown in cognitive processing (Stine-Morrow, Miller, & Hertzog, 2006). This may be compensated for by the implementation of a "risky" reading strategy in which older adults are more likely to guess upcoming words than young adults in order to maximise reading speeds, resulting in this age group frequently making larger forwards movements in the text, but often needing to move their eyes backwards when these guesses prove wrong (Rayner et al., 2006; 2009).

These changes may also be due, at least partially, to age-related declines in the visual system. Advanced age is associated with numerous changes in the eye and brain that can lead to a significant decline in visual functioning (Owsley, 2011). In particular, older adults show reduced sensitivity to fine visual detail (e.g. edges, features) in comparison to young adults (Crassini, Brown, & Bowman, 1988; Owsley, 2011), which may lead to a greater use of more coarse-scale information (e.g. global cues to shape, length) during reading (Jordan, McGowan, & Paterson, 2014; Paterson, McGowan, & Jordan, 2013b,c). Older age is also associated with greater effects of visual crowding (a reduced ability to identify objects in clutter, Bouma, 1970), particularly outside of the fovea (Scialfa, Cordazzo, Bubric, & Lyon, 2012). These visual declines are likely to affect older adults' basic visual processing when reading. One consequence of this may be that adult age may modulate the extent to which the visual properties of a text affect reading.

In English and most other alphabetic languages, words are separated by spaces. In addition to providing readers with a highly salient (coarse-scale) cue to word boundaries, interword spaces also help guide eye movements, and reduce crowding of the exterior letters of words, making words easier to identify (Perea & Acha, 2009; Rayner, Fischer, & Pollatsek, 1998). Removing or obscuring interword spaces slows reading markedly, and disrupts eye movement behaviour across a variety of measures (e.g. Paterson & Jordan, 2010; Perea & Acha, 2009; Rayner, et al., 1998). Indeed, while readers typically land slightly to the left of centre of a word in a location known as the preferred viewing position (Rayner, 1979), removing or filling interword spaces produces a shift in landing positions towards the beginning of the word, indicating that saccade targeting is disrupted under these conditions (Perea & Acha, 2009; Rayner et al., 1998). Furthermore, studies that have included an embedded target word which was either high or low in frequency showed that removing or filling interword spaces increases the size of the word frequency effect (Paterson & Jordan, 2010; Perea & Acha, 2009; Rayner, et al., 1998). As word frequency is a reliable indicator of lexical processing, increases in the size of the word frequency effect indicates that these manipulations disproportionately affect the processing of lower frequency words (Rayner et al., 1998), suggesting that unspaced and filled space text disrupts normal processes of word identification.

Research investigating the effects of removing or filling interword spaces has been conducted mostly with children and young adult readers, but two recent studies examined effects for older adult readers (McGowan, White, Jordan, & Paterson, 2014; Rayner, Yang, Schuett, & Slattery, 2013). These studies showed that both young and older adults had difficulties reading unspaced and filled space text, although this difficulty was greater for the older adults. The indication, therefore, is that older adults obtain greater benefits from the use of interword spaces. Word frequency manipulations showed that removing or filling interword spaces disrupted word identification similarly for the young and older adults. Thus, the greater reading difficulty experienced by the older adults for unspaced and filled space text was not due to added disruption to lexical processing for older adults, but most likely due to particular impairment of older adults' visual processing. Indeed, older adults have reduced sensitivity to fine-scale information and greater effects of visual crowding (Crassini et al., 1988; Owsley, 2011; Scialfa et al., 2012). This may mean that older adults rely especially heavily on interword spaces during reading as these provide coarse-scale cues for word segmentation and reduce the crowding of the exterior letters of words. Consistent with this account, McGowan et al. (2014) reported that filling interword spaces with closed squares (■), which provide a coarse-scale cue to word boundaries, resulted in a much smaller age difference in eye movement behaviour than filling interword spaces with open squares (□). The open squares did not provide a particularly salient cue to word boundaries and included features similar to those found in letters (horizontal and vertical lines) and so were likely to produce greater effects of visual crowding.

The studies by McGowan et al. (2014) and Rayner et al. (2013) clearly show that older adults are more sensitive than young adults to the availability of spatial information in text. Of course, in normal reading (of English at least) unspaced text is not usually encountered. However, readers often encounter variations in the size of interword space due, for example, to differences between fonts and the effects of text justification. This begs the question of whether older adults may also be more sensitive than young adults to more subtle but naturalistic changes in the size of interword spaces. In particular, older adult readers may have greater difficulty compared to young adult readers when interword spacing is present but smaller than normal, due to increased visual crowding. By contrast, older adult readers may benefit more than young adult readers from larger than normal interword spacing due to reduced effects of visual crowding. Indeed, such effects would have important implications for the everyday reading of older adults.

Only a few studies have examined the effects of changes to the size of interword spaces on eye movements during reading, and none have examined effects of age. Moreover, the few studies that have investigated this issue (in young adults) have either examined the effects of large-scale changes in word spacing rather than the more subtle variations encountered during every day reading, or have examined the combined effects of subtle changes in interword spacing with changes in intraword spacing (the spaces in between letters), making the effects of variations in word spacing difficult to ascertain. For example, Rayner et al. (1998) reported that adding two extra spaces between each word produced a numerical trend towards shorter average fixation durations. Similarly, Drieghe, Brysbaert, and Desmet (2005) reported that adding an extra space following a target word produced shorter reading times on that word. This benefit was observed for the reading of text but not the scanning of z-strings, and so the authors suggested that this decrease in fixation durations may be attributable to a reduction in crowding for the exterior letters of the word rather than effects on low-level oculomotor control. This may be because reducing crowding facilitates early word encoding processes (Perea & Gomez, 2012a). Paterson and Jordan (2010) found that inserting extra spaces between both letters *and* words (to produce large-scale increases in both inter- and intraword spacing) produced more fixations, longer reading times on a target word, and larger word frequency effects. More subtle increases to both inter- and intraword spacing (consistent with what is typically encountered during every day reading) have been found to produce more but shorter fixations, but no consistent effects for sentence reading times (Perea & Gomez, 2012b; Slattery & Rayner, 2013). On the other hand, condensing both inter- and intraword spaces produces more and longer fixations (Slattery & Rayner, 2013). These findings suggest that subtle changes to the size of interword spaces may affect eye movements during reading. However, as the effects cannot be disentangled from the effects of changes to intraword spacing size in these studies, the independent contribution of changes to interword spacing cannot be ascertained.

In summary, at present it is not known, 1) how subtle but naturalistic changes in the size of interword spacing affect eye movement behaviour during reading (independently of changes in intraword spacing size), and 2) whether the eye movement performance of older adults, compared to that of young adults, shows greater sensitivity to subtle variations in word spacing. Accordingly, the present experiment sought to address these issues by examining how the eye movements of young and older adults were affected by changes in the size of the spaces between words when reading. These findings will extend those reported by McGowan et al (2014) and Rayner et al (2013) by more fully revealing how well young and older adults' reading performance adjusts to changes in spatial information in text.

In the present experiment, young and older adults read sentences in which interword spacing was normal, condensed so that it was half its normal size, or expanded so that it was 1.5 times its normal size. Condensed interword spacing may have the advantage of bringing upcoming words closer to the point of fixation, and thus parafoveal processing may be facilitated due to improvements in acuity. However, condensed interword spaces could also reduce the saliency and ease with which word boundaries are identified, and increase crowding for the exterior letters of words by increasing their proximity to the adjacent word. In contrast, expanded interword spaces may have the benefit of making words more salient visual objects and reducing the effects of crowding for the exterior letters of words, but would also project upcoming text further into the parafovea where visual acuity is lower, which may be detrimental to parafoveal processing. We had no prior expectations as to whether these subtle changes in interword spacing size would be beneficial or disruptive to the reading of young adults. However, given that older adults experience greater effects of crowding (Scialfa et al., 2012), and have an increased reliance on coarse-scale cues for word segmentation (McGowan et al., 2014), it was expected that this age group may benefit from the reduction in crowding and the provision of an even more salient cue for word segmentation that expanded interword spaces would afford. Furthermore, as older adults may have a smaller perceptual span (Rayner et al., 2009), the potential cost of reduced parafoveal processing when interword spaces are expanded may be reduced for this age group.

In order to examine how these subtle changes to the size of interword spaces affect reading and, moreover, whether this changes with older age, the effects of these manipulations on the eye movement behaviour of young and older adult readers was assessed. Embedded target words that were either high or lower in frequency enabled an examination of whether changes to interword spacing size affected word identification processes, since this would manifest as changes in the size of the word frequency effect. If older adults are more sensitive to changes in the size of interword spaces, interactions between age and spacing would be expected. Moreover, if word identification is affected by age, then further interactions with word frequency would occur.

Method

Participants: Fifteen young adults (*M* = 19.9 years, range = 18 – 25) and 15 older adults (*M* = 72.5 years, range = 67 - 80) were recruited from the University of Leicester and the surrounding community. All were native English speakers, did not report any history of dyslexia, and wore glasses if needed. Visual abilities were assessed at the viewing distance using an ETDRS chart (Ferris & Bailey, 1996), and for contrast sensitivity using a Pelli-Robson chart (Pelli, Robson, & Wilkins, 1988). All participants were screened to ensure an acuity of at least 20/40, but compared to the young adults, the older adults had lower acuity (young adults, M = 20/17; older adults, M = 20/28; $t(28) = 6.23$, $p < .001$) and lower contrast sensitivity (young adults, M = 2.00; older adults, M = 1.90; $t(28) = 3.34$, $p = .002$). The two age groups did not differ on years of education (young adults, M = 15.5 years, range = 12-21 years; older adults, M = 16.9 years, range = 10-24 years; $t(28) = 1.46$, $p > .05$) or hours spent reading per week (young adults, M = 11.4 h/week, range = 2-27 h/week; older adults, M = 16.4, range = 5-60 h/week; $t(28) = 1.24$, $p > .05$)

- (Insert Figure 1 about here) -

Materials & Design: Stimuli consisted of 120 sentences that included a high or lower frequency target word (taken from White, Staub, Drieghe, Liversedge, 2011). Word frequencies were calculated using the Zipf frequency scale (log10 of frequency per billion words) based on the SUBTLEX database (van Heuven, Mandera, Keuleers, & Brysbaert, 2014). The target words comprised 60 high frequency nouns with a mean frequency of 5.24 and 60 lower frequency nouns with a mean frequency of 3.36. As expected, frequencies for these two groups of words differed significantly, $t(59) = 30.48$, $p < .001$. Target words were arranged into pairs of high and low frequency words matched for length (mean = 5.3 characters, range = 4-6 characters) and predictability (none predicted in a cloze task), and presented in 60 pairs of sentences, for which each pair shared a neutral initial sentence frame. These sentences were shown in one of three display conditions; normal interword spacing, condensed interword spacing (in which the interword spaces were half the standard size), and expanded interword spacing (in which interword spaces were 1.5 times the standard size; see Figure 1). This formed a 2 (age groups – young, older) x 3 (display conditions – normal, condensed, expanded) mixed design, with the additional factor of word frequency (high, low) for the word-level analyses. Each combination of initial sentence frame and target word was viewed once by each participant, and a Latin Square design ensured that within each participant group each sentence frame and target word combination was seen equally often in the three spacing conditions. These 120 experimental items were preceded by six practice items (two per condition). Experimental items were shown in a pseudorandom order to ensure that none of the sentence pairs were presented close together.

Apparatus: An Eyelink 1000 tower mounted eye-tracker was used to record gaze location every millisecond. Viewing was binocular, but only the right eye was tracked. Stimuli were displayed in courier new font on a 20 inch monitor with a screen resolution of 1024x768. Stimuli were presented in high contrast as black text (RGB 0,0,0) on a very light grey background (RGB 225, 225, 225). At the 80cm viewing distance used in the study, there were approximately 3.3 characters per degree of visual angle (11 pixels per character).

Procedure: At the beginning of the experiment participants were informed that they should read for comprehension. Prior to the presentation of the trials, a three-point horizontal calibration procedure was conducted, and the accuracy of the calibration was checked prior to the presentation of each trial. On correctly fixating a cross the sentence was automatically presented, with the first letter of the sentence replacing the cross. Participants were instructed to press a response key once they had finished reading the sentence. 25% of the sentences were followed by a yes/no comprehension question, to which participants responded using a button response.

Results and Discussion

Comprehension accuracy was high (M = 93%, and above 80% for all participants), and there were no differences between the age groups or spacing conditions, and no interactions (all Fs < 2, all ps > .1). Following standard procedures, fixations shorter than 80ms or longer than 1200ms were removed (3.1% of fixations). For word-level analyses, trials were excluded if a blink preceded or followed a fixation on the target (accounting for 1.1% of trials for young adults and 5.3% of trials for older adults). The remaining data were analysed using Analysis of Variance (ANOVA) with factors age group (young, older) and display condition (normal, condensed, expanded) for sentence-level analyses, and including frequency (high, low) as an additional factor for word-level analyses. Variance was computed across participants (F_1) and items (F_2), and effects were deemed reliable only if significant by both participants and items. The Greenhouse-Geisser correction was used where appropriate. For all analyses, the design was mixed for F_1 analyses and within-items for F_2 analyses. Pairwise comparisons were performed using the Bonferroni correction ($p <$. 05 for significant effects).

- (Insert Tables 1 and 2 about here) -

Sentence-level Analyses

The following measures were examined for the sentence-level analyses: reading time (the time taken from when the sentence was first presented to when the button was pressed to terminate the trial); average fixation duration (the average duration of all fixational pauses); number of fixations (total number of fixational pauses); number of regressions (number of backwards movements either within or between words); and progressive saccade length (the average distance, in characters, moved by the eyes during forward movements). Table 1 shows means for the sentence-level measures and Table 2 reports the associated ANOVA statistics.

Older adults had longer sentence reading times, made more regressions, and had longer progressive saccades than young adults. These findings are consistent with findings from previous studies (e.g. Kliegl et al., 2004; McGowan et al., 2014; Paterson et al., 2013a; Rayner et al., 2006).

There were main effects of interword spacing size for all the sentence-level measures with the exception of the number of regressions. Pairwise comparisons revealed that relative to normal text, condensed text produced longer fixation durations, and a numerical trend towards a smaller number of fixations. This effect of condensing interword spaces was, however, small, and did not result in a significant difference in reading times compared to normal text. By comparison, expanded text produced more but shorter fixations than either normal or condensed text. Furthermore, expanded text produced a small but significant increase in reading times compared to normal or condensed text.

Whereas condensed text resulted in shorter progressive saccades than normal text, expanded text resulted in longer progressive saccades than normal text. Furthermore, the size of these differences in saccade length (-0.5 characters for condensed text and +0.4 characters for expanded text in comparison to normal text) show a striking similarity to the size of the changes in spacing size (-0.5 characters for condensed text and +0.5 characters for expanded text in comparison to normal text). Although it is not possible to draw a direct parallel between these numbers (since this would involve the erroneous assumption that saccades always move from one word to the next), the indication is that readers modify the size of their saccades to accommodate small changes in interword spacing size.

The two way interaction of age and spacing type did not approach significance for any measures. This indicates that older adults were able to adapt their eye movement behaviour to subtle changes in interword spacing as effectively as young adults.

In summary, sentence-level analyses show that changes in the size of interword spaces had small, but reliable effects on eye movements. Condensed text produced longer but (numerically) fewer fixations than normal text, whereas expanded text produced shorter but more fixations than normal text, and a small, but significant increase in overall reading times. The finding that fixations were longer for condensed than normal text, and shorter for expanded than normal text, may be due to changes in crowding of exterior letters of words. This may have been greater for condensed text (due to the increased proximity of adjacent words) but smaller for expanded text (due to the increased distance between adjacent words). Crowding may have influenced fixation durations by affecting early encoding processes

(Perea & Gomez, 2012a), consistent with previous findings showing that more extreme changes to interword spacing affect fixation durations for the reading of text, but not the scanning of z-strings (Drieghe et al., 2005). Whereas condensed text produced fewer fixations than normal text, expanded text produced more fixations than normal text. This may reflect differences in how frequently words were skipped (and thus how many fixations were made overall) due to changes in the ease of parafoveal processing. Indeed, there was a main effect of spacing for first-pass word skipping ($F_1(2, 58) = 18.53$, $\eta_\pi^2 = .390$, $p < .001$; $F_2(2, 118) = 26.26$, $\eta_\pi^2 = .308$, $p < .001$). Skipping rates were higher for condensed than normal text, which may reflect a facilitation of parafoveal processing due to upcoming words being brought closer to fixation (where they could be seen more easily) when interword spaces were made smaller. On the other hand, skipping rates were lower for expanded than normal text. This may be due to a difficulty in parafoveal processing due to upcoming words being projected further from fixation (where they could be seen less easily) when interword spaces were made larger.

Condensing and expanding interword spaces affected progressive saccade length relative to normal text and the size of these adjustments in saccade size was very similar to the size of the changes in interword spacing. The indication, therefore, is that readers adjusted forward saccade length to accommodate changes in interword spacing, which is consistent with other findings showing that readers can flexibly modify saccade size when the spacing between words is increased (Drieghe et al., 2005) or the size of the text is changed (Morrison & Rayner, 1981).

Finally, there were no interactions between age and spacing for any of the global measures. This indicates that changes to the size of interword spaces affected the eye movement behaviour of young and older readers similarly.

- (Insert Tables 3 and 4 about here) -

Word-level analyses

Word-level analyses were computed for the high or lower frequency target words, for which the following measures were analysed: first fixation durations (duration of the first fixation on the critical word during first pass reading, i.e. excluding words that were initially skipped); gaze durations (summed duration of first pass fixations on the word); total reading times (sum of all fixation durations on the word); refixation probability (proportion of trials in which more than one fixation was made on the word during first pass); number of fixations (total number of fixations on the word); and word skipping probability (the proportion of trials in which the word did not receive a first pass fixation). In addition, landing positions (the character on which the reader's initial first pass fixation landed within the word, for which the space preceding the word was counted as one character regardless of size) are considered separately below.

Table 3 shows means for the word-level measures and Table 4 reports the associated ANOVA statistics. Older adults produced longer first fixation durations and total reading times, and higher skipping rates for target words than young adults. These results are consistent with findings from previous research (e.g. Kliegl et al., 2004; McGowan et al., 2014; Paterson et al., 2013a; Rayner et al., 2006).

There were significant main effects of spacing for the number of fixations and word skipping probabilities. Pairwise comparisons revealed that expanded text produced a reliably lower probability of word skipping and a numerical trend towards more fixations than normal or condensed text. Crucially, these findings are in line with findings from the sentence-level analyses.

Consistent with previous investigations of the word frequency effect (e.g. Rayner, Sereno, & Raney, 1996; White, 2008), lower frequency words received longer first fixation durations, gaze durations, and total reading times, more fixations and refixations, and were skipped less often than higher frequency words. Word frequency also interacted with age in gaze durations, and the number of fixations. Pairwise comparisons revealed significant effects of frequency for both age groups for both measures. Thus, in order to examine these interactions *t*-tests were conducted in which the size of the frequency effect was entered as the dependent variable. The size of the frequency effect was larger for older adults than for young adults for both gaze durations, $t_1(28) = 2.28$, $p < .05$; $t_2(59) = 2.66$, $p < .05$, and the number of fixations, $t_1(28) = 2.17$, $p < .05$; $t_2(59) = 2.10$, $p < .05$. It has been argued previously that larger frequency effects arise from difficulties in word identification disproportionately affecting lower frequency words (e.g. Rayner et al., 1998). The present findings show that older adults made disproportionately more and longer fixations for lower frequency words compared to young adults. This indicates, therefore, that the older adults had more difficulty identifying words during reading.

Consistent with the results from the sentence-level analyses, there were no interactions between age and spacing, indicating that older adults were able to adapt to changes in interword spacing size as well as young adults. There also were no reliable interactions between spacing and target word frequency, and no three way interactions between age, spacing and target word frequency. These findings indicate that increases or decreases in the size of interword spaces did not affect word identification processes for either the young or older adults.

In sum, word-level analyses showed small, but reliable effects of changes to the size of interword spacing on eye movement behaviour. When spaces were expanded, readers made more fixations on the target word and were less likely to skip this word than when spaces were normal. This may be because larger interword spaces made parafoveal processing more difficult by projecting upcoming words further from fixation (where acuity is poorer), leading to words being skipped less often and thus fixated more. However, changes to the size of interword spacing did not affect word identification processes, indicating that these effects are likely to be pre-lexical. Furthermore, these changes affected the eye movements of the two age groups to a similar extent, confirming the findings of the sentence-level analyses that older adults are able to adapt their eye movements to subtle changes in interword spacing as well as young adults.

Landing positions of initial fixations on target words: The mean length of target words was 5.3 letters (range = 4-6 letters) and the average landing position was 2.9 characters in from the left boundary of words. Readers therefore fixated slightly to the left of the centre of words, consistent with previous observations that readers tend to systematically fixate a preferred viewing location between the beginning and middle letters of words (e.g. Rayner, 1979). There was no main effect of spacing, indicating that expanding or condensing interword spaces did not impair readers' abilities to target saccades towards the preferred viewing location. Thus, consistent with the pattern of results for progressive saccade amplitudes in the sentence-level analyses, these results indicate that readers were able to effectively modify their saccade lengths according to the interword spacing size used. Initial landing positions also did not differ between young and older adults, indicating that older adults were able to target their eye movements as well as young adults. This is in agreement with previous findings that oculomotor control is preserved during older age (Paterson et al., 2013a). There was, however, a significant interaction between age and word frequency. Pairwise comparisons revealed that the effect of word frequency was significant for older but not young adults. However, given the small size of this (unexpected) effect (one fifth of a character), additional evidence should be sought before drawing strong conclusions about this finding.

General Discussion

The present experiment investigated the effects of subtle increases and decreases to the normal spaces between words on the eye movements of young and older adult readers. Thus, this study extended previous findings that showed older adults have more difficulty than young adults when reading unspaced text (McGowan et al., 2014; Rayner et al., 2013). In line with previous findings (e.g. Kliegl et al., 2004; McGowan et al., 2014; Paterson et al., 2013; Rayner et al., 2006), older adult readers had longer sentence reading times, made more and longer fixations, more regressions, skipped words more often, and made longer progressive saccades than young adult readers. Older adult readers also produced larger word frequency effects than young adults. Consistent with previous findings (Kliegl, et al., 2004; Rayner, et al., 2006) this indicates that older adults had greater difficulty in identifying words during reading.

Changing the size of interword spaces produced small, but reliable effects on sentence reading times and eye movement behaviour. In particular, compared to normal text, increasing the spacing between words produced longer sentence reading times, more but shorter fixations, and reduced the likelihood of words being skipped. The finding that fixation durations were shorter when interword spaces were expanded compared to normal is consistent with findings that larger increases to interword spacing also produce shorter fixation durations than normal spacing (Drieghe et al., 2005; Rayner et al., 1998). Expanding interword spaces increases the distance between adjacent words, which may reduce crowding for their exterior letters. This reduction in crowding may speed up early encoding stages, resulting in shorter fixation durations (Perea & Gomez, 2012a). However, larger than normal spaces also project upcoming words further into the parafovea where words can be seen less easily. This may produce difficulties in parafoveal processing, leading to words being skipped less frequently, and thus more fixations. Condensing interword spaces, on the other hand, resulted in fewer but longer fixations, and a higher probability of words being skipped than normal text. Condensing interword spaces increases the proximity of adjacent words, which may produce greater effects of crowding. These increased effects of crowding may lead to longer fixation durations by slowing down early encoding stages of word recognition (Perea & Gomez, 2012a). However, the increased proximity between fixated and upcoming words also brings upcoming words closer to fixation where they can be seen more easily. This may facilitate parafoveal processing, leading to more words being skipped, and thus fewer fixations.

Despite these effects on eye movement behaviour, the results indicate that readers can adapt the targeting of their saccades to accommodate changes in the size of interword spaces. Indeed, condensing interword spaces (such that upcoming words were closer to fixation) resulted in shorter progressive saccade lengths than normal text, whereas expanding interword spaces (such that upcoming words were further from fixation) resulted in longer progressive saccade lengths than normal text. The sizes of these differences in progressive saccade length showed a striking similarity to the size of the changes in interword spacing, and furthermore, there were no reliable effects of these changes to interword spacing size on initial landing positions for the target word. Thus, these findings indicate that readers can flexibly accommodate subtle changes in interword spacing size when planning saccades.

Changes in interword spacing size did not affect word identification processes for either young or older adults, as shown by a lack of interactions between spacing type and frequency, or any three-way interactions with age. Thus, although varying the size of interword spaces did affect eye movements, this did not appear to be due to any additional difficulties in lexical processing. Instead, these results indicate that modulating the size of interword spaces has a pre-lexical effect on eye movement control. For example, visual crowding (the effects of which would have been increased in the condensed condition but reduced in the expanded condition) may have affected early stages of feature encoding (Perea & Gomez, 2012a).

Finally, contrary to expectations, no interactions between spacing type and age were found for word-level or sentence-level measures. Thus, older adult readers were no more sensitive to subtle and naturalistic changes to the size of interword spaces than young adult readers. Furthermore, older adult readers were able to modify their saccades to suit the size of interword spacing as successfully as young adult readers, indicating that the ability to flexibly adapt eye movement behaviour in response to subtle changes in the spatial layout of a text is similar across these adult age groups. Thus, consistent with previous findings that saccade targeting is preserved into older age (Paterson et al., 2013a), the present study indicates that declines in the reading performance of healthy adults later in life are not due to impairment to oculomotor control.

The absence of any interactions between age and spacing was surprising given previous findings that the reading of older adults is more disrupted by the removal of interword spaces than for young adults (McGowan et al., 2014; Rayner et al., 2013). The findings for unspaced text in those studies may be attributed to older adults gaining more benefit than young adults from the coarse-scale cue for word segmentation and the reduction in crowding of the exterior letters of words that interword spaces provide. Indeed, in comparison to young adults, older adults experience greater effects of crowding, and typically have a reduced sensitivity to fine scale detail which may lead to a greater reliance on coarse-scale information (Crassini et al., 1988; Owsley, 2011; Paterson et al., 2013b,c; Scialfa et al., 2012). Importantly, however, the current results show that as long as some space information is present, the eye movement behaviour of older adults is resilient to small changes in interword spacing size. Thus, in line with previous evidence that basic control of eye movements does not deteriorate during older age (Paterson et al., 2013a), the present study indicates that older adults are able to adapt their eye movements to subtle changes in the spatial layout of a text as successfully as young adults.

In conclusion, subtle changes to the size of interword spaces have small, but reliable effects on eye movement behaviour. However, these changes affect young and older adults similarly, and both age groups appear able to modify their saccades to adjust to these changes in word spacing. Thus, the indication is that older adults are able to adapt to the subtle variations in interword spacing size that are encountered frequently during every day reading as well as young adults.

Disclosure statement

No conflicts of interest arise from this research.

References

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature, 226*(5241), 177-178.

Crassini, B., Brown, B., & Bowman, K. (1988). Age-related-changes in contrast sensitivity in central and peripheral retina. *Perception, 17*(3), 315-332.

Drieghe, D., Brysbaert, M., & Desmet, T. (2005). Parafoveal-on-foveal effects on eye movements in text reading: Does an extra space make a difference? RID A-3910-2011. *Vision Research, 45*(13), 1693-1706.

Ferris, F.L., & Bailey, I.L. (1996). Standardizing the measurement of visual acuity for clinical research studies. *Ophthalmology, 103*, 181-182.

Jordan, T.R., McGowan, V.A., & Paterson, K.B. (2014). Reading with filtered fixations: Age differences in the effectiveness of low-level properties of text within central vision. *Psychology and Aging, 29,* 229-235.

Kliegl, R., Grabner, E., Rolfs, M., & Engbert, R. (2004). Length, frequency, and predictability effects of words on eye movements in reading. *European Journal of Cognitive Psychology, 16*(1-2), 262-284.

McGowan, V.A., White, S.J., Jordan, T.R., & Paterson, K.B. (2014). Aging and the use of interword spaces during reading: Evidence from eye movements. *Psychonomic Bulletin & Review, 21,* 740-747.

Morrison, R.E., & Rayner, K. (1981). Saccade size in reading depends upon character spaces and not visual angle. *Perception & Psychophysics, 30,* 395-396.

Owsley, C. (2011). Aging and vision. *Vision Research, 51*(13), 1610-1622.

Paterson, K. B., & Jordan, T. R. (2010). Effects of increased letter spacing on word identification and eye guidance during reading. *Memory & Cognition, 38*(4), 502-512.

Paterson, K. B., McGowan, V. A., & Jordan, T. R. (2013a). Aging and the control of binocular fixations during reading. *Psychology and Aging, 28*(3), 789-795.

Paterson, K. B., McGowan, V. A., & Jordan, T. R. (2013b). Effects of adult aging on reading filtered text: Evidence from eye movements. *PeerJ, 1*, e63

Paterson, K. B., McGowan, V. A., & Jordan, T. R. (2013c). Filtered text reveals adult age differences in reading: Evidence from eye movements. *Psychology and Aging, 28*(2), 352-364.

Pelli, D. G., Robson, J. G., & Wilkins, A. J. (1988). The design of a new letter chart for measuring contrast sensitivity. *Clinical Vision Sciences, 2*(3), 187-199.

Perea, M., & Acha, J. (2009). Space information is important for reading. *Vision Research, 49*(15), 1994-2000.

Perea, M., & Gomez, P. (2012a). Increasing interletter spacing facilitates encoding of words. *Psychonomic Bulletin & Review, 19*(2), 332-338.

Perea, M., & Gomez, P. (2012b). Subtle increases in interletter spacing facilitate the encoding of words during normal reading. *Plos One*, *7*(10), e47568.

Rayner, K. (1979). Eye guidance in reading - fixation locations within words. *Perception, 8*(1), 21-30.

Rayner, K., Castelhano, M. S., & Yang, J. (2009). Eye movements and the perceptual span in older and younger readers. *Psychology and Aging, 24*(3), 755-760.

Rayner, K., Fischer, M. H., & Pollatsek, A. (1998). Unspaced text interferes with both word identification and eye movement control. *Vision Research*, *38*(8), 1129-1144.

Rayner, K., Reichle, E., Stroud, M., Williams, C., & Pollatsek, A. (2006). The effect of word frequency, word predictability, and font difficulty on the eye movements of young and older readers. *Psychology and Aging, 21*, 448-465.

Rayner, K., Sereno, S. C., & Raney, G. E. (1996). Eye movement control in reading: A comparison of two types of models. *Journal of Experimental Psychology-Human Perception and Performance, 22*(5)

Rayner, K., Yang, J., Schuett, S., Slattery, T. J. (2013). Eye movements of older and younger readers when reading unspaced text. *Experimental Psychology, 60*, 354-361.

Scialfa, C.T., Cordazzo, S., Bubric, K., & Lyon, J. (2013). Aging and visual crowding. *Journals of Gerontology Series B: Psychological Sciences and Social Science, 6,* 522-528.

Slattery, T. J., & Rayner, K. (2013). Effects of intraword and interword spacing on eye movements during reading: Exploring the optimal use of space in a line of text. *Attention Perception & Psychophysics, 75*(6), 1275-1292.

Stine-Morrow, E. A. L., Miller, L. M. S., & Hertzog, C. (2006). Aging and self-regulated language processing. *Psychological Bulletin, 132,* 582–606.

Van Heuven, W.J.B., Mandera, P., Keuleers, E., & Brysbaert, M. (2014). Subtlex-UK: A new and improved word frequency database for British English. *Quarterly Journal of Experimental Psychology, 67(6),* 1176-1190.

White, S.J. (2008). Eye movement control during reading: Effects of word frequency and orthographic familiarity. *Journal of Experimental Psychology: Human Perception and Performance, 34(1),* 205-223.

White, S.J., Staub, A., Drieghe, D., & Liversedge, S.P. (2011). Word frequency effects during reading: Binocular fixations and the distribution of fixation durations. *European Conference on Eye Movements*, Marseille, France.

Table 1. Means and standard errors (in parentheses) for the sentence-level analyses. SE = Spacing effect (means of the condensed/expanded conditions minus the mean of the normal condition).

		Normal	Condensed	SE	Expanded	SE
Reading Times (ms)	Young	2327 (169)	2306 (168)	-21	2387 (180)	60
	Older	2857 (144)	2866 (135)	9	2928 (143)	71
Fixation Duration	Young	209 (6)	215 (6)	6	203 (6)	-6
	Older	226 (7)	232 (7)	6	221 (7)	-4
Fixation Count	Young	10.2 (0.6)	9.9 (0.6)	-0.3	10.6 (0.6)	0.4
	Older	11.2 (0.5)	11.1 (0.5)	-0.1	11.6 (0.5)	0.4
Number of Regressions	Young	1.4 (0.2)	1.4 (0.2)	0.0	1.5 (0.2)	0.1
	Older	2.9 (0.3)	2.9 (0.3)	0.0	2.9 (0.3)	0.0
Progressive Saccade Amplitude (chars)	Young	7.4 (0.3)	7.0 (0.3)	-0.4	7.9 (0.3)	0.5
	Older	9.6 (0.5)	9.1 (0.5)	-0.5	9.9 (0.5)	0.3

Table 2. Statistical values for analyses of the sentence-level measures.

		Sentence Reading Time		Average Fixation Duration		Number of Fixations		Number of Regressions		Progressive Saccade Amplitude	
		F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2
Age	df	1, 28	1, 59	1, 28	1, 59	1, 28	1, 59	1, 28	1, 59	1, 28	1, 59
	F	6.1*	722.4***	3.6	297.6***	1.9	196.6***	19.3***	1160.2***	13.1***	2207.8***
	η_π^2	.178	.924	.114	.835	.063	.769	.408	.952	.319	.974
Display	df	2, 56	2, 118	2, 56	2, 118	2, 56	2, 118	2, 56	2, 118	2, 56	2, 56
	F	4.6*	4.9**	40.2***	40.9***	15.2***	21.2***	0.26	0.24	102.9***	104.8***
	η_π^2	.141	.076	.59	.409	.352	.264	.009	.004	.786	.640
Age x Display	df	2, 56	2, 118	2, 56	2, 118	2, 56	2, 118	2, 56	2, 118	2, 118	2, 118
	F	0.18	0.20	0.23	0.26	0.25	0.38	0.20	0.27	1.1	0.87
	η_π^2	.006	.003	.008	.004	.009	.006	.007	.005	.036	.015

* = $p < .05$, ** = $p < .01$, *** = $p < .001$.

Table 3. Means and standard errors (in parentheses) for the word-level analyses. SE = Spacing effect (means of the condensed/expanded conditions minus the mean of the normal condition), FE = Frequency effect (means of the lower frequency condition minus the mean of the high frequency condition). Word length = 4-6 letters, M = 5.3.

		Normal		Condensed			Expanded			
		High	Low	High	Low	SE	High	Low	SE	FE
First Fixation Duration (ms)	Young	198 (6)	218 (7)	205 (8)	224 (7)	6	201 (8)	215 (7)	0	17
	Older	214 (6)	245 (10)	225 (7)	245 (6)	6	211 (6)	243 (11)	-3	28
Gaze Duration (ms)	Young	212 (7)	240 (10)	218 (10)	248 (9)	7	217 (13)	247 (9)	6	29
	Older	228 (8)	262 (12)	238 (9)	275 (11)	11	226 (8)	284 (13)	9	44
Total Reading Time (ms)	Young	231 (12)	275 (15)	239 (11)	283 (12)	8	246 (18)	281 (13)	11	41
	Older	295 (11)	337 (14)	298 (12)	360 (22)	14	284 (16)	366 (25)	11	62
Refixation Probability (%)	Young	8.4 (1.8)	12.3 (2.3)	6.2 (2.4)	11.7 (2.6)	-1.2	7.4 (2.7)	16.8 (3.0)	2.0	6.3
	Older	8.4 (2.4)	9.2 (2.0)	7.2 (1.9)	14.4 (3.0)	2.2	8.5 (3.2)	18.2 (3.2)	4.7	6.0
Number of Fixations	Young	1.03 (0.06)	1.17 (0.06)	1.01 (0.06)	1.17 (0.07)	-0.1	1.12 (0.07)	1.26 (0.05)	0.09	1.5
	Older	1.13 (0.07)	1.34 (0.06)	1.07 (0.05)	1.38 (0.09)	-0.1	1.18 (0.08)	1.44 (0.11)	0.08	2.6
Word-Skipping Probability (%)	Young	17.1 (3.9)	12.4 (2.5)	16.7 (3.4)	14.7 (3.6)	1.0	12.7 (3.2)	6.0 (1.8)	-5.5	-4.5
	Older	24.6 (5.1)	19.5 (3.4)	29.0 (4.0)	20.5 (3.7)	2.8	21.7 (4.4)	17.0 (3.3)	-2.6	-6.1
Landing Position (characters)	Young	3.0 (0.1)	2.9 (0.1)	3.1 (0.1)	3.0 (0.1)	0.1	2.8 (0.2)	2.9 (0.1)	-0.1	-0.1
	Older	2.9 (0.1)	3.0 (0.1)	3.0 (0.1)	3.1 (0.1)	0.1	2.7 (0.1)	3.1 (0.1)	-0.1	0.2

Table 4. Statistical values for analyses of the word-level measures.

		First Fixation Duration		Gaze Duration		Total Reading Time		Refixation Probability		Number of Fixations		Word Skipping Probability		Landing Position	
		F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2	F_1	F_2
Age	df	1, 28	1, 58	1, 28	1, 58	1, 28	1, 59	1, 28	1, 59	1, 28	1, 59	1, 28	1, 59	1, 28	1, 59
	F	5.16^{*}	67.6^{***}	3.19	45.4^{***}	12.66^{***}	89.0^{***}	0.04	1.19	2.33	24.7^{***}	4.37^{*}	51.3^{***}	0.02	0.01
	η_π^2	.156	.542	.012	.443	.311	.601	.001	.020	.077	.295	.135	.221	.001	.001
Display	df	2, 56	2, 116	2, 56	2, 116	2, 56	2, 118	2, 56	2, 118	2, 56	2, 118	2, 56	2, 118	2, 56	2, 118
	F	3.76^{*}	2.88	2.65	3.47^{*}	1.20	3.41^{*}	2.66	3.90^{*}	4.38^{*}	6.62^{**}	7.95^{***}	7.81^{***}	3.03	2.37
	η_π^2	.118	.048	.087	.057	.041	.055	.087	.064	.135	.101	.221	.117	.098	.039
Frequency	df	1, 28	1, 58	1, 28	1, 58	1, 28	1, 59	1, 28	1, 59	1, 28	1, 59	1, 28	1, 59	1, 28	1, 59
	F	52.5^{***}	42.8^{***}	127.2^{***}	74.6^{***}	113.4^{***}	40.2^{***}	49.74^{***}	18.4^{***}	63.9^{***}	40.4^{***}	12.7^{***}	14.1^{***}	1.87	3.64
	η_π^2	.652	.429	.820	.567	.802	.405	.640	.244	.695	.407	.313	.193	.063	.059
Age x Display	df	2, 56	2, 116	2, 56	2, 116	2, 56	2, 118	2, 56	2, 118	2, 56	2, 118	2, 56	2, 118	2, 56	2, 118
	F	0.07	0.16	0.15	0.05	0.11	0.09	0.72	0.64	0.01	0.05	0.42	0.16	0.02	0.28
	η_π^2	.003	.003	.005	.001	.004	.002	.025	.011	.001	.001	.015	.003	.001	.005
Age x Frequency	df	1, 28	1, 58	1, 28	1, 58	1, 28	1, 59	1, 28	1, 59	1, 28	1, 59	1, 28	1, 59	1, 28	1, 59
	F	2.65	6.79^{*}	4.35^{*}	6.45^{*}	4.77^{*}	3.14	0.04	0.19	4.93^{*}	4.96^{*}	0.30	0.36	4.56^{*}	4.03^{*}
	η_π^2	.086	.106	.134	.102	.145	.051	.001	.001	.150	.078	.011	.006	.140	.005
Display x Frequency	df	2, 56	2, 116	2, 56	2, 116	2, 56	2, 118	2, 56	2, 118	2, 56	2, 118	2, 56	2, 118	2, 56	2, 118
	F	0.53	0.66	1.76	0.94	0.73	1.10	2.85	2.74	0.57	0.59	0.03	0.05	1.78	0.62
	η_π^2	.018	.011	.059	.016	.025	.018	.092	.046	.020	.010	.001	.001	.060	.011
Age x Display x Frequency	df	2, 56	2, 116	2, 56	2, 116	2, 56	2, 118	2, 56	2, 118	2, 56	2, 118	2, 56	2, 118	2, 56	2, 118
	F	0.96	0.99	1.40	1.29	1.70	1.56	0.34	0.13	0.26	0.15	1.02	0.76	0.87	0.32
	η_π^2	.033	.017	.048	.022	.057	.026	.012	.002	.009	.003	.035	.013	.005	.005

* = $p < .05$, ** = $p < .01$, *** = $p < .001$.

Figure 1. An Example Sentence in each Display Condition

Figure 1.

Normal

He knew that the small room would be really useful for storage.

Condensed

He knew that the small room would be really useful for storage.

Expanded

He knew that the small room would be really useful for storage.