Filtered Text Reveals Adult Age Differences in Reading:

Evidence from Eye Movements

Kevin B. Paterson*

Victoria A. McGowan

Timothy R. Jordan

Faculty of Medicine, Biological Sciences and Psychology

University of Leicester

United Kingdom, LE1 9HN

*Corresponding Author

Running title: Filtered Text Reveals Adult Age Differences in Reading

ABSTRACT

Sensitivity to certain spatial frequencies declines with age and this may have profound effects on reading performance. However, the spatial frequency content of text actually used by older adults (aged 65+), and how this differs from that used by young adults (aged 18-30), remains to be determined. To investigate this issue, the eye movement behavior of young and older adult readers was assessed using a gaze-contingent moving-window paradigm in which text was shown normally within a region centered at the point of gaze while text outside this region was filtered to contain only low, medium, or high spatial frequencies. For young adults, reading times were affected by spatial frequency content when windows of normal text extended up to 9 characters wide. Within this *processing region*, the reading performance of young adults was affected little when text outside the window contained either only high or medium spatial frequencies but was disrupted substantially when text contained only low spatial frequencies. By contrast, the reading performance of older adults was affected by spatial frequency content when windows extended up to 18 characters wide. Moreover, within this extended processing region, reading performance was disrupted when text contained any one band of spatial frequencies but was disrupted most of all when text contained only high spatial frequencies. These findings indicate that older adults are sensitive to the spatial frequency content of text from a much wider region than young adults, and rely much more than young adults on coarse-scale components of text when reading.

Key Words: Eye Movements, Reading, Aging, Spatial Frequencies.

The ability to read is of fundamental importance for people to function effectively in everyday life. However, numerous studies indicate that, compared to young adults (typically aged 18-30), older adults (aged 65+) often find reading more difficult (e.g., Kemper, Crow, & Kemtes, 2004; Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner, Castelhano, & Yang, 2009; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; see also Laubrock, Kliegl, & Engbert, 2006). In this research, older readers typically read more slowly, make more and longer eye fixations, and more regressions (backwards movements in the text) than younger adults. This age-related difference is widely attributed to sensory and cognitive decline associated with normal aging and may lead older adults to adopt different reading strategies to compensate for their poorer processing of text (Rayner et al., 2006, 2009). However, the precise nature of this decline, and how it affects the reading performance of older adults, remains to be determined.

A major consideration is that visual abilities change with normal aging, and older adults experience a range of subtle visual deficits that may affect their use of the spatial frequency content of words during reading (e.g., Akutsu, Legge, Ross, & Schuebel, 1991; Elliott, Yang, & Whitaker, 1995; Owsley, 2011). In particular, although words may appear to be composed only of letters, words are actually complex visual stimuli containing a variety of spatial frequencies (e.g., Allen, Smith, Lien, Kaut, & Canfield, 2009; Ginsburg, 1986; Lovegrove, Bowling, Badcock, & Blackwood, 1980; Martin, Cornelissen, Fowler, & Stein, 1993; Patching & Jordan, 2005a, 2005b; Blakemore & Campbell, 1969; Robson, 1966), ranging from low spatial frequencies that may be useful for determining the overall layout of text, including the size, shape, and location of words, to high spatial frequencies that may help specify individual letter features and letters. Consequently, if the change in visual abilities associated with normal aging leads to a change in the functionality of various spatial frequencies when reading, young and older adults may differ in their use of the spatial frequency content of text, and this may have important consequences for understanding adult age-related changes in reading performance.

The spatial frequencies used by young and older adult readers remain to be determined.

However, a progressive change in visual abilities occurs with normal aging and appears predominantly as a decline in sensitivity for fine-scale visual information (e.g., Derefelt, Lennerstrand, & Lundh, 1979; Elliott, 1987; Elliott et al., 1995; Higgins, Jaffe, Caruso, & deMonasterio, 1988; Owsley, Sekuler, Siemsen, 1983; for a recent review, see Owsley, 2011). This loss of sensitivity to information supplied by higher spatial frequencies is widely attributed to a combination of optical changes and changes in neural transmission with increasing age, but the precise effect of these changes on older adults' reading ability is unknown.

To investigate this issue, we used a variation of the gaze-contingent moving window paradigm (e.g., McConkie & Rayner, 1975, 1976; Rayner & Bertera, 1979; Rayner et al., 2009). In the standard paradigm, participants are required to read lines of text in which only a narrow window of text around each point of gaze is shown normally during reading, and text outside this window is changed by replacing each letter with an x or another character to conceal letter identities while preserving word length and punctuation. It is well-established that text is read by making a series of short and rapid eye movements separated by brief fixational pauses during which information is acquired from the text (for overviews of research on eye movements in reading, see Rayner, 1998, 2009). Consequently, in the moving window paradigm, the location of the window is yoked to the direction of the readers' gaze so that when readers' eyes move to fixate a new word, the window moves in synchrony with these eye movements and a new window of normal text is displayed at each new gaze location and all letters outside this new window are changed. These display changes can be made so rapidly that readers report that the window appears to move in perfect synchrony with their eyes.

The standard version of this paradigm has been invaluable in revealing how much information is acquired on each fixation (referred to as a reader's *perceptual span*) by varying the size of the moving window, and so determining what size of window of normal text is required for reading performance to be indistinguishable from that observed for regular textual displays. Previous research indicates that young adults acquire information from a region that extends about 3-4 characters to the left of the point of gaze and up to 15 characters to the right (e.g., McConkie & Rayner, 1976; Rayner & Bertera, 1979). But within this perceptual span, detailed letter information is obtained from a much smaller region that extends only about 7 or 8 characters to the right of the point of gaze (Rayner, Well, Pollatsek, & Bertera, 1982; Underwood & McConkie, 1985). Research using the standard paradigm has also shown that beginning readers (Häikiö, Bertram, Hyönä, & Neimi, 2009; Rayner, 1986) and readers with dyslexia (Rayner, Murphy, Henderson, & Pollatsek, 1989) have a smaller perceptual span than skilled young adult readers. Of particular relevance to the present research, however, is more recent research that investigated adult age differences in the size of the perceptual span (Rayner et al., 2009; see also Rayner, Castelhano, & Yang, 2010; Risse & Kleigl, 2011). In this research, Rayner et al. (2009) used moving windows in which either only the fixated word was shown normally, the fixated word and either one or two words to its right were shown normally, or the fixated word and one word to its left were shown normally, and each of the other letters in words were replaced by an x. Reading times for young adults were the same as for regular textual displays only when the fixated word and two words to its right were shown normally, consistent with young adults having a perceptual span that is asymmetric to the right of fixation (e.g., McConkie & Rayner, 1976; Rayner & Bertera, 1979). In contrast, compared to when just the fixated word was shown normally, older adults' reading times were shorter when the fixated word and either one word to its right or left were shown normally (with no additional benefit of showing two words to the right of the fixated word normally). Rayner et al. (2009) took these findings to indicate that the perceptual span for older adult readers is smaller and more symmetrical around the point of gaze than for young adult readers. The findings therefore suggest that young and older adults differ in their use of the visual information present in text at particular locations around the point of gaze.

Accordingly, to reveal adult age differences in the use of spatial frequencies at various locations around the point of gaze during reading, we modified the moving window paradigm so that all text outside each window was filtered to contain only its low, medium, or high spatial frequency content. The width of these windows (and so the amount of text that remained normal) was gradually increased outward from the point of fixation to determine the use of different spatial frequencies at various eccentricities (see Figure 1 for example sentences). This technique enabled an assessment of the use of different spatial frequencies at particular locations away from the point of gaze to be made whilst preserving the identity of words, letters, and information about word length and word boundaries. The 3 bands of spatial frequencies we used are known to be influential in word recognition (e.g., Patching & Jordan, 2005a, 2005b) and so were well-suited to revealing age-related differences in the use of the spatial frequency content of text during reading. Without knowing how visual information on each side of the point of gaze may contribute to reading (and whether this, like the perceptual span, is asymmetric to the right of fixation for younger adults), we took a pragmatic approach for this study and (as in the original moving window paradigm; McConkie & Rayner, 1975) used windows that extended symmetrically around the point of gaze. These windows ranged from just 3 characters wide, centered at the point of gaze, to 15 characters wide in Experiment 1, and to 21 characters wide in Experiment 2. In this way, the regions within which normal text was available around the point of gaze during reading were carefully manipulated so that the reliance placed by young and older readers on each type of spatial frequency content at various eccentricities could be determined.

------------------------------Figure 1-----------------------------

The logic of this approach was straightforward (see also Chung & Tjan, 2009; Leat & Munger, 1994; Legge, Pelli, Rubin, & Schleske, 1985; Patching & Jordan, 2005a, 2005b). If readers require spatial frequency content in particular regions around from the point of gaze to read normally, normal reading performance will be impaired when text in these regions lacks these spatial frequencies. Moreover, if young and older readers place different requirements on the spatial frequencies present in these regions to read normally, these differences should be revealed by the effectiveness of each band of spatial frequencies at sustaining normal reading performance in each age group.

GENERAL METHOD

Participants. Sixty-four adults from the University of Leicester and the local community participated in the experiments. Of these, 16 young adults and 16 older adults participated in two sessions in Experiment 1, and another 16 young adults and 16 older adults participated in two sessions in Experiment 2. All participants were native English speakers, had a similar educational background, reported an interest in reading and that they read frequently, and had normal or corrected to normal vision (an inclusion criterion equivalent to Snellen acuity of 20/30 for high contrast distance acuity was employed). A summary of these characteristics and of the assessment of participants' visual abilities is shown in Table 1. High and low contrast distance acuity was assessed using a Bailey-Lovie Eye Chart (Bailey & Lovie, 1976), and high and low contrast near acuity (for normal reading distance) was assessed using the MNREAD Acuity Chart (Mansfield, Ahn, Legge, & Luebker, 1993). We report participants' performance in these assessments by transforming log mar values into equivalent Snellen values. Self-report measures were used to assess participants' years in formal education and to estimate the number of hours spent reading for study or pleasure each week.

------------------------------Table 1------------------------------

Design and Materials. 160 sentences were constructed. These were between 49 and 65 characters long, inclusive. In both experiments, the sentences were displayed in 1 of 16 conditions (normal + 5 levels of window size x 3 levels of filtering) in which each sentence was shown either entirely as normal or the spatial frequency content was filtered outside a moving window centered at each point of fixation. Experiment 1 used a moving window of either 3, 6, 9, 12, or 15 characters wide, and Experiment 2 used a moving window of either 3, 9, 15, 18, or 21 characters wide. Text inside each moving window was normal and text outside each window was filtered to leave only the low, medium, or high spatial frequency content of the original text. This filtered text was created using MATLAB. Text was filtered into one of 3 different, 1-octave wide bands with peak spatial frequencies of 3.5, 6.7, and 11.1 cycles per degree (cpd) and low-pass and high-pass cut-off frequencies of 2.6-5.2, 5.0-10.0, and 8.3-16.6 cpd, for low, medium, and high spatial frequency content respectively. This was achieved by point-wise multiplication in the frequency domain with fourth-order high- and low-pass Butterworth filters. The Butterworth filter is a mathematically tractable filter shape that avoids the problems of ringing associated with other filter shapes with a sharp cut-off (e.g., for further details, see Patching & Jordan, 2005a, 2005b). The resulting sentence displays were randomized and selected using a Latin square design so that each participant saw an equal number of sentences in each display condition but saw each sentence only once. This enabled all sentences to be shown equally often in each display condition across participants but avoided repetition of any sentence for any participant. Sixteen practice items (1 per condition) were presented at the start of each session.

Apparatus and Procedure. Viewing was binocular and eye movements were recorded from each participant's right eye with an Eyelink 2K eye-tracker, using a chin and forehead rest. This eye-tracker has a spatial resolution of .01° and the position of each participant's right eye was sampled at 1000 Hz using corneal reflection and pupil tracking. Sentences were displayed on a 19 inch monitor at 100 Hz. At the viewing distance of approximately 85 cm, 4 letters subtended approximately 1.2°. Custom software ensured that the window moved in close synchrony with eye movements and display changes were made within 12-15 ms. The phenomenological experience of all participants was that each window moved in perfect synchrony with the eyes during reading.

At the beginning of the experiment, participants were instructed to read normally and for comprehension. The eye-tracker was then calibrated. At the start of each trial, a fixation square (equal in size to 1 character) was presented at the left of the screen. Once the participant fixated this location accurately, a sentence was presented, with the first letter of the sentence replacing the square. Participants pressed a response key when they finished reading each sentence. The sentence was then replaced by a comprehension question, to which participants responded. Calibration was checked between trials and the tracker was recalibrated as necessary. Each experiment session lasted approximately 40 minutes (plus the time taken to perform visual assessments).

EXPERIMENT 1

Experiment 1 compared the reading performance of young and older adults using text shown entirely as normal or presented in a moving window paradigm in which text was shown as normal only within a window of between 3 and 15 characters wide centered at the point of gaze, and text outside each window was filtered to contain only low, medium, or high spatial frequencies.

RESULTS AND DISCUSSION

The most comprehensive and informative measure of reading performance in moving window experiments is total sentence reading time (e.g., McConkie & Rayner, 1975; Rayner & Bertera, 1979) and this is shown in Figure 2. This represents the overall amount of time taken to read each sentence. Other measures are sometimes also discussed and so mean fixation duration (the average length of the fixational pauses during reading), number of fixations (the number of these fixational pauses), number of regressions (backwards movements in the text), and progressive saccade length are also reported (see Table 2). Progressive saccade length refers to the span of the forward eye movements during reading and this is reported as the mean number of characters traversed by progressive saccades (for detailed discussion of eye movement measures, see Rayner, 1998, 2009). Young and older adults showed no differences in accuracy for questions presented after each trial to assess comprehension (young adults=97.4% correct, older adults=97.8% correct, $t<1$). In addition, comprehension accuracy did not differ for sentences displayed in each filter and window condition compared to sentences displayed entirely as normal for either young or older adults (all Fs<1.4). Moreover, when sentences were displayed entirely as normal, reading times did not differ between young and older adults (young adults=2785 ms, older adults=2762 ms, $t<1$), indicating that the two groups read normal text displays equally quickly. However, differences in the influence of spatial frequency content and window size for each age group were apparent.

------------------------------Figure 2-----------------------------

-------------------------------Tables 2 & 3-------------------------------

Analysis of Variance (ANOVA) was used to compare reading times and eye movement measures for normal displays with those for each window (3, 6, 9, 12, or 15 characters wide) and age group (young adult, older adult) separately for each spatial frequency band (low, medium, high), computing error variance over participants (F_1) and sentences (F_2) and using the Greenhouse-Geisser correction where appropriate. Table 3 provides a summary of these statistical analyses, and reports main effects of age group and window size, and interactions of these factors, separately for each band of spatial frequencies. Planned pair-wise comparisons were performed using Bonferroni-corrected *t*-tests. Further analyses used Bonferroni-corrected *t*-tests to compare across the different bands of spatial frequencies for each window size, separately for each age-group. These pairwise comparisons are reported for analyses performed across participants but the same pattern of effects was obtained for analyses performed across sentences.

The moving window paradigm revealed key differences in the use of spatial frequency content of text by young and older adult readers, which were observed clearly in the reading times for sentences. As Table 3 indicates, there was a main effect of age-group for all types of spatial frequency content, due to overall longer reading times for older adults, and main effects of window size that were qualified by interactions of window size and age-group for each band of spatial frequencies. For young adults, reading times (relative to normal displays) for windows 3-9 characters wide were slowed by low spatial frequencies (ps<.05), but unaffected by medium and high spatial frequencies (ps>.30). For 3-9 character windows, reading times were slower for low spatial frequencies than for medium and high spatial frequencies (ps<.05). No other differences were significant (ps>.10). By comparison, older adults' reading times (relative to normal displays) were slowed by all spatial frequencies for all window sizes (ps<.05). For 3-character windows, reading times were slower for low spatial frequencies than for medium spatial frequencies (p<.05) but, for all window sizes, reading times were slowest of all for high spatial frequencies (ps<.05). No other differences were significant.

These findings show that the distance from a reader's point of gaze at which different spatial frequency content affected reading times (the processing region) differed substantially between age groups. For young adults, reading times were affected by the spatial frequency content of text outside areas extending up to 9 characters wide at the point of fixation but were insensitive to spatial frequency manipulations beyond this processing region. However, for older readers, the processing region extended further from fixation, and older adults' reading times were sensitive to the spatial frequency content of text even outside an area 15 characters wide around the point of fixation.

Furthermore, within each processing region, the effect of spatial frequency content was markedly different for young and older readers. In particular, the reading times of young adults were slowed only when text within the processing region contained just low spatial frequencies, and text containing medium or high spatial frequencies had no effect on normal reading times. Moreover, medium and high spatial frequencies produced similar reading times for all window sizes, suggesting that young adults used these two types of spatial frequency content extensively and with similar effect for reading. By comparison, the reading performance of older adults was disrupted most when text within the processing region contained only high spatial frequencies, and this effect was observed for all window sizes. Text containing only low or medium spatial frequencies was also disruptive at each window size, but this disruption was always less than that observed for high spatial frequencies. Indeed, although low spatial frequencies were more disruptive than medium spatial frequencies when displayed closest to fixation (3 character windows), low and medium spatial frequencies produced similar effects on reading times at all other distances from fixation, suggesting that these two types of spatial frequency content were generally more useful for older adults when reading, with comparable effects.

Data from the other eye movement measures broadly complement these findings for reading times (see Tables 2 & 3). Main effects of age-group were obtained for fixation durations and number of fixations (for high spatial frequencies only), due to older adults making more and longer fixations. Main effects of window size were qualified by interactions with age-group for medium and high spatial frequencies for fixation durations, and for all spatial frequencies for number of fixations, number of regressions, and progressive saccade length. For young adults, fixation durations and number of fixations showed that normal reading performance was affected by the spatial frequency content of text outside windows extending up to 9 characters wide around the point of gaze, and that most disruption was caused by low spatial frequencies (*p*s<.01), and only this spatial frequency content affected the number of fixations made (*p*s>.80 for medium and high spatial frequencies). Young adults also made shorter progressive saccades when text outside 3 and 6 character windows contained just low spatial frequencies (*p*s<.05), and when windows up to 12 characters wide contained just high spatial frequencies (*p*s<.05). Thus, although young adults require high spatial frequency content in text around the point of gaze to read normally, young adults make shorter progressive saccades when only this spatial frequency content is present in text beyond this region. This is likely to be due to reduced sensitivity to higher spatial frequencies towards peripheral vision (e.g., Crassini, Brown, & Bowman, 1988) which, in turn, would impair perception of cues to word length and word boundaries, and cause difficulty in saccadic programming (e.g., Pollatsek & Rayner, 1982).

For older adults, the pattern of findings for fixation durations, number of fixations, and progressive saccade length showed that each type of spatial frequency content outside the moving window affected processing for all window sizes (*p*s<.01). However, most disruption was observed when text contained only high spatial frequencies (*p*s<.05), and the disruption caused by medium and low spatial frequency content was smaller and comparable across a wide range of window sizes. Older adults also made more regressions when the moving window was small (3-characters wide) and only low spatial frequencies were available (*p*<.001). This suggests that while all types of spatial frequency content affected fixation duration, number of fixations, and progressive saccade length, older adults found that low spatial frequencies provided a more useful basis for making informative regressions.

It was apparent from the findings of Experiment 1 that the reading performance of older adults was sensitive to the spatial frequency content of text outside the moving window even when the window of normal text was the maximum used in this experiment (15 characters wide). Therefore, to gain a clearer understanding of the extent of the processing region for older adults, in Experiment 2 we conducted a further assessment of reading performance using the same stimuli and procedures as Experiment 1 but with larger window sizes, ranging from 3 to 21 characters wide.

EXPERIMENT 2

As in Experiment 1, the reading performance of young and older adults was compared using text shown entirely as normal or presented in displays in which normal text was shown only within a moving window centered at the point of gaze, and text outside each window contained only low, medium, or high spatial frequency content.

RESULTS AND DISCUSSION

As in Experiment 1, the focus was on reading time (see Figure 3) but mean fixation duration, number of fixations, number of regressions, and progressive saccade length are also reported (see Table 4). Comprehension accuracy was high, and was a little better for older adults than young adults (young adults=98.2% correct, older adults=99.3% correct, $t(30)=2.33$, $p<.05$) but did not differ for sentences displayed in each filter or window condition compared to sentences shown normally for either the young or older adults (all Fs<2.0). As in Experiment 1, reading times for normal displays did not differ between young and older adults (young adults=2643 ms, older adults=2454 ms, $t<1$). However, as in Experiment 1, substantial differences in the influence of spatial frequency content and window size for each age group were apparent.

-------------------------------Figure 3------------------------------

-------------------------------Tables 4 & 5------------------------------

Analyses were conducted as in Experiment 1, with the exception that window sizes were now 3, 9, 15, 18, or 21 characters wide. Table 5 provides a summary of statistical analyses using ANOVA, and reports main effects of age group and window size, and interactions of these factors, separately for each band of low, medium, and high spatial frequencies.

ANOVAs for sentence reading times produced a main effect of age-group for high spatial frequencies only, due to overall longer reading times for older adults. Main effects of window size for all bands of spatial frequencies were qualified by significant interactions of window size and age-group for medium and high spatial frequencies. For young adults, reading times (relative to normal displays) were slowed by low spatial frequency content for windows 3 and 9 characters wide (*p*s<.001), but not by medium and high spatial frequency content for any windows (*p*s>.24). For windows 3 and 9 characters wide, reading times were slower for low spatial frequencies than for medium or high spatial frequencies. No other differences were significant. For older adults, reading times (relative to normal displays) were slowed by low and medium spatial frequencies for 3-15 character windows (*p*s<.01), and by high spatial frequencies for all window sizes (*p*s<.05). For 3 character windows, reading times were slower for low spatial frequency content than for medium spatial frequency content (*p*s<.001) but, for windows 3-18 characters wide, reading times were slowest of all for high spatial frequency content (*p*<.05). No effect of spatial frequency content was observed for the 21 character window (*p*s>.40).

Therefore, as in Experiment 1, the reading times in Experiment 2 revealed important differences in the influence of the spatial frequency content of text on reading by young and older adults. In particular, the distance from the point of gaze at which reading performance was sensitive to different spatial frequency content (the processing region) again differed substantially between age groups and affected their reading times. For young adults, normal reading times were sensitive to the spatial frequency content of text outside windows up to 9 characters wide, and showed no sensitivity to spatial frequency content when wider windows of normal text were shown. Indeed, for windows wider than 9 characters, each type of spatial frequency content (i.e., low, medium, high) produced normal reading speeds. In contrast, for older adults, the regions within which normal reading showed sensitivity to the spatial frequency content of text extended much further from fixation, and the larger window sizes used in Experiment 2 showed sensitivity by older adults to low and medium spatial frequency content for windows up to 15 characters wide, and high spatial frequencies for all window sizes. Consequently, even at these distances from fixation, restricting the spatial frequency content of text affected reading.

Experiment 2 also underscored the finding that, within the processing region, reading by young and older adults showed markedly different sensitivity to spatial frequency content. For young adults, reading was slowed considerably when text in the processing region contained only low spatial frequencies, whereas medium and high spatial frequencies within this region had little effect on reading times. By comparison, the reading of older adults was slowed, sometimes substantially, when text outside windows up to 21 characters wide contained only high spatial frequencies, while low and medium spatial frequency content within this region was generally less disruptive.

Other eye movement measures, particularly fixation durations and number of fixations, produced findings broadly comparable with the findings for reading times (see Tables 4 & 5). These measures, along with number of regressions, did not produce main effects of age-group, and progressive saccade length produced a main effect of age-group for low spatial frequencies only. However, all of the measures produced main effects of window size that were qualified by interactions of window size and age-group for medium and high spatial frequencies for fixation duration and number of fixations, and for all spatial frequencies for progressive saccade length and number of regressions.

For young adults, an increase in fixation durations and number of fixations again showed that normal reading performance was affected by the spatial frequency content in text outside windows extending up to 9 characters wide around the point of gaze ($ps<.01$). As with reading times, most disruption was caused by low spatial frequency content (and only this spatial frequency content affected the number of fixations made). Young adults also made shorter progressive saccades when text outside 9 character windows contained just low spatial frequencies ($ps<.001$), and when text outside windows up to 15 characters contained just high spatial frequencies ($ps<.05$). This was broadly consistent with findings for progressive saccades in Experiment 1 showing that, although young adults require fine-scale information about words around the point of gaze to read normally, they make shorter progressive saccades when only high spatial frequency content is present in text beyond this region. The findings therefore provide further evidence that reduced sensitivity to high spatial frequencies that is natural outside foveal vision impairs perception of cues to word length and word boundaries, and that this causes difficulty in saccadic programming.

For older adults, the pattern of findings for fixation duration and number of fixations showed that normal reading performance was affected by each type of spatial frequency content (i.e., low, medium, high) for windows extending up to 9 characters wide around the point of gaze (ps<.05), and by high spatial frequencies for windows extending up to 15 characters wide (i.e., a slightly smaller region than indicated by the sentence reading times; ps<.05). Most disruption within this region was caused by high spatial frequency content. Therefore, as in the reading time data, there was clear evidence that reduced sensitivity to high spatial frequencies disrupted older adults' processing of text within a broad region around the point of gaze. The findings for progressive saccade length also expand on the findings from Experiment 1 by showing that when performance for a wider range of window sizes is examined, older adults made shorter progressive saccades when text outside a 21 character region around the point of fixation contains either medium or high spatial frequency content (ps<.001). This effect for older adults is similar to the effect of high spatial frequencies on progressive saccade length observed for younger adults. Consequently, reduced sensitivity to higher spatial frequencies towards the periphery appears to be particularly detrimental to saccadic programming by young and older adults, arguably by impairing perception of cues to word length and word boundaries. Finally, older adults again made more regressions when the moving window was small (3-characters wide) and only low spatial frequency content was available outside each window (ps<.01). Thus, as in Experiment 1, it appears that while all types of spatial frequency content affected fixation duration, number of fixations, and progressive saccade length, older adults found that low spatial frequencies provided a more useful basis for making informative regressions.

GENERAL DISCUSSION

The differences between young and older readers revealed in this study indicate adult age-related changes in the use of the spatial frequency content of text during reading. These differences were investigated by assessing the reading performance of young and older adults in a gaze-contingent moving-window paradigm that used symmetrical moving windows in which text within each window was shown normally and text outside each window was filtered so that it contained only sparse spatial frequency content (low, medium, or high). The greater effectiveness of medium and high spatial frequencies for young adult readers suggests that much of the information used by this age group for reading is provided by detailed analyses of letter fragments and individual letters within a relatively narrow processing region in text and cannot be provided by low spatial frequencies. By comparison, the widespread effectiveness of low and medium spatial frequency content of text for older readers suggests that more of the information used by this age group for reading is derived from coarse-scale analyses of whole words and letters, and is obtained from a much wider processing region, across which high spatial frequencies are not as effective. Indeed, even at the closest point to fixation (3-character window) where visual acuity is highest (e.g., Riggs, 1965), displaying text with only high spatial frequency content produced the greatest disruption to reading for older adults.

These age-related shifts in the use of the spatial frequency content of text may reflect a wide-spread, age-related decline in sensitivity to various scales of spatial frequency, particularly those associated with detailed analysis (e.g., Derefelt et al., 1979; Elliott, 1987; Higgins et al., 1988; Owsley et al., 1983; for a review, see Owsley, 2011). Indeed, although the older readers in our study showed good visual abilities when tested, their reading abilities still showed lowered sensitivity to the fine-scale information in text associated with normal aging. Consequently, the particular difficulty older adults had in reading text that contained only high spatial frequency content is consistent with this widespread decline in processing fine-scale visual content. However, despite clear differences in the influence of different spatial frequencies on reading, both age groups produced near identical levels of reading times when text was displayed normally. This suggests that changes in sensitivity to various spatial frequencies caused by normal aging need not necessarily produce a decline in reading ability. Instead, it appears that, as readers get older, they develop an adaptive shift in the use of different spatial frequencies so that information that is more visible becomes the most important for reading, and this information is acquired from a broad processing region. It should be noted, however, that visual impairments are widespread in older populations and so any capacity for older adults to read normally is likely to require a certain level of natural or corrected visual ability.

The near-identical reading times we observed for the two age groups when text was displayed normally contrast with previous research showing that older adults typically read more slowly than younger adults (e.g., Kemper et al., 2004; Kliegl et al., 2004; Rayner et al., 2009; Rayner et al., 2006). One component of this may be an apparent trade-off between number of fixations and fixation duration, due to older adults making slightly fewer but longer fixations than young adults, and longer progressive saccades when reading normal text displays (see also Laubrock et al., 2006; Rayner et al., 2006). However, the unimpaired reading speeds of these older adults may also reflect the emphasis placed on good visual abilities in the present research and the stringency with which participants' visual abilities were screened. Indeed, the careful screening of visual abilities is of particular concern for research on older adults' reading, as visual impairments are prevalent in this population, and often go unnoticed until accurate assessment is conducted (for a recent review, see McGowan, Paterson, & Jordan, 2012).

The findings of this study concerning young adult readers are broadly compatible with other findings showing that young adults acquire information primarily from within a restricted perceptual span when reading (e.g., Rayner & McConkie, 1975, 1976), and that within this perceptual span they acquire detailed letter information from only a narrow region extending no more than 7-8 characters to the right of the point of gaze (Rayner et al., 1982). Efforts to improve the visibility of text and increase the amount of letter information acquired by young adult readers, either by varying the distance of the reader from the text display (Morrison & Rayner, 1981), or by progressively magnifying text away from the point of gaze by increasing the font size of each successive letter outside a window of text shown normally (Miellet, O'Donnell, & Sereno, 2009), have no appreciable effect on reading performance. Accordingly, these findings have led researchers to conclude that the perceptual span is governed primarily by attentional demands, and not by acuity limitations (e.g., Reichle, Liversedge, Rayner, & Pollatsek, 2009). These researchers argue that text is processed in a serial manner in which detailed information about words is acquired from a narrow region around the point of gaze and only more gross information about word length and word boundaries is obtained from beyond this region. Our findings for young adults are compatible with this view but reveal more fully the nature of the spatial frequency content that young adults encode from text and use for reading. In particular, the findings show young adults' reading is sensitive to the spatial frequency content of text within a very narrow region and that normal reading is impaired when text within this region contains only low spatial frequency content and so lacks detailed information about individual letters and letter features likely to be important for word identification.

The findings for older adult readers from the present research indicate that they are sensitive to the spatial frequency content of text across a broader span. Indeed, the indication from the present study is that the region in which readers are sensitive to the spatial frequency content of text is substantially wider (in fact, about double) for older readers than for young readers. Previous research using a standard moving window paradigm in which each of the letters in words outside the moving window is replaced by an x indicates that older adults have a smaller and more symmetric perceptual span than young adults (Rayner et al., 2009). The present results do not challenge this view but what they do show is that, within a region encompassed by the perceptual span, young and older adults differ in their sensitivity to the spatial frequency content of text. In particular, whereas young adults require fine-scale information from a narrow processing region at the center of gaze that may help the serial processing of word identities, older adults acquire more coarse-scale features from text across a broader region. For example, acquiring visual information about the identities of words from a wider region within the perceptual span may aid reading by allowing the processing of visual cues from a greater number of words, which in turn may provide more contextual information. The extent to which older adults benefit more from contextual cues during reading is controversial (e.g., Madden, 1988; Stine-Morrow, Miller, Gagne, & Hertzog, 2008; Federmieir & Kutas, 2005; Federmieir, Kutas, & Schul, 2010), and eye movement research suggests that older adults do not benefit more from the contextual predictability of words than younger adults (Kliegl et al., 2004; Rayner et al., 2006). Nevertheless, effects of loss of sensitivity to higher spatial frequencies on word processing may be offset by a greater use of contextual information, consistent with the view that older readers compensate for processing difficulties by greater reliance on discourse context (e.g., Stine-Morrow et al., 2008). Moreover, the use of spatial frequency content of text from a wider region may be assisted by the allocation of attention to wider areas of text and may reflect adult age differences in how young and older adults allocate attention during reading. Indeed, the present findings resonate with the view that young and older adults differ in how they allocate attention within the perceptual span (e.g., Risse & Kleigl, 2011), and that older adults may deploy attention across a wider region of text during reading as part of an adaptive strategy to compensate for their generally poorer processing of text.

The effects of spatial frequencies on the length of progressive saccades shed further light on the contribution of different spatial frequency information to the reading process. In particular, progressive saccades were shorter than normal for both young and older adults when text outside a wide range of moving windows was composed of just high spatial frequencies, and so it appears that when text in parafoveal vision contained just high spatial frequency content, this impaired saccadic programming. There is substantial evidence that although older adults have reduced sensitivity to high spatial frequencies compared to younger adults for central viewing presentations, both age groups show reduced sensitivity to high spatial frequency information (and spared sensitivity to lower spatial frequency information) for peripheral presentations (e.g., Crassini et al., 1988). Consequently, as the length of progressive saccades was less affected by medium and low spatial frequencies, it seems that the more coarse-scale components of text in parafoveal visual contribute most to the programming of progressive saccades, and our findings suggest that relatively gross information about word length and word boundaries is used to program saccadic eye movements during reading by both young and older adults (for other evidence of the importance of word boundaries for eye guidance, see Pollatsek & Rayner, 1982; Paterson & Jordan, 2010; Rayner, Fischer, & Pollatsek, 1998).

Finally, it was clear that, within each age group, different spatial frequencies produced similar levels of reading performance, which suggests that the information derived from different spatial frequencies in text can be equally effective for reading. For example, for young adults, medium and high spatial frequency content may provide different cues to the more detailed components of text but both appear to support normal reading, and produced similar patterns of effects in both reading times and in the number and length of fixations. In a similar vein, for older adults, low and medium spatial frequencies may provide different cues to the more coarse-grained components of text but showed evidence of being equally effective. However, for older adults, normal reading performance occurred with any single band of spatial frequency only for windows greater than 15 characters wide for low and medium spatial frequencies, and windows greater than 18 characters for high spatial frequencies, suggesting that older adults generally use a broader range of spatial frequency content for normal reading. But the patterns of performance observed with both age groups support the view that reading is likely to involve information from a range of spatial scales, so that a wide range of spatial frequencies may independently (and collaboratively) activate processes of word perception during reading (e.g., Allen & Madden, 1990; Allen et al., 2009; Boden & Giaschi, 2009; Jordan, 1990, 1995; Leat & Munger, 1994; Legge et al., 1985; Patching & Jordan, 2005a, 2005b). From our findings, the region within which the spatial frequency content of text affects normal reading, and the weighting attached by readers to different spatial frequencies within this processing region, may both change substantially with aging. However, although aging leads to important changes in reading behaviour, it seems that adaptive responses to a changing visual input may help older adults read efficiently well into later life.

ACKNOWLEDGEMENTS

This research was funded by the Ulverscroft Foundation and an Economic Research Foundation Professorial Fellowship to Tim Jordan and a British Academy Mid-Career Fellowship to Kevin Paterson. We are grateful to Philip T. Smith for advice on an earlier draft. We also thank Keith Rayner and two anonymous reviewers. Correspondence may be addressed to Kevin Paterson (kbp3@le.ac.uk) or Timothy Jordan (Prof.TimJordan@le.ac.uk).

REFERENCES

Allen, P.A., & Madden, D.J. (1991). Evidence for a parallel input serial analysis model of word processing. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 48-64.

Allen, P.A., Smith, A.F., Lien, M.C., Kaut, K.P., & Canfield, A. (2009). A multi-stream model of visual word recognition. *Attention, Perception, & Psychophysics*, *71*, 281-296.

Akutsu, H., Legge, G.E., Ross, J.A., & Schuebel, K. (1991). Psychophysics of reading: X. Effects of age related changes in vision. *The Journals of Gerontology, Series B: Psychological Sciences and Social Sciences*, *46*, 325-331.

Bailey, I.L., & Lovie, J.E. (1976). New design principles for visual acuity letter charts. *American Journal of Optometry and Physiological Optics*, *53*, 740-745.

Blakemore, C., & Campbell, F.W. (1969). Adaptation to spatial stimuli. *Journal of Physiology, 200*, 11-13.

Boden, C., & Giaschi, D. (2009). The role of low-spatial frequencies in lexical decision and masked priming. *Brain and Cognition*, *69*, 580-591.

Chung, S.T.L., & Tjan, B.S. (2009). Spatial-frequency and contrast properties of reading in central and peripheral vision. *Journal of Vision*, 9(16), 1-19.

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

Derefelt, G., Lennerstrand, G., & Lundh B. (1979). Age variations in normal human contrast sensitivity. *Acta Ophthalmologica*, *57*, 679–690.

Elliott, D.B. (1987). Contrast sensitivity decline with ageing: A neural or optical phenomenon? *Ophthalmic and Physiological Optics*, *7*, 415-419.

Elliott, D.B., Yang, K.C., & Whitaker, D. (1995). Visual acuity changes throughout adulthood in normal, healthy eyes: Seeing beyond 6/6. *Optometry and Vision Science*, *72*, 186-191.

Federmeier, K. D., & Kutas, M. (2005). Aging in context: Age-related changes in context use during language comprehension. *Psychophysiology*, *42*, 133-141.

Federmeier, K.D., Kutas, M., & Schul, R. (2010). Age-related and individual differences in the use of prediction during language comprehension. *Brain and Language, 115*, 149-161.

Ginsburg, A.P. (1986). Spatial filtering and visual form perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of human perception and human performance* (Vol. 2, chap. 34, pp. 1-41). New York: Wiley.

Häikiö, T., Bertram, R., Hyönä, J., & Neimi, P. (2009). Development of the letter identity span in reading: Evidence from the eye movement moving window paradigm. *Journal of Experimental Child Psychology*, *102*, 167-181.

Higgins, K.E., Jaffe, M.J., Caruso, R.C., & deMonasterio, F.M. (1988). Spatial contrast sensitivity: effects of age, test-retest, and psychophysical method. *Journal of the Optical Society of America*, *5*, 2173-2180.

Jordan, T.R. (1990). Presenting words without interior letters: Superiority over single letters and influence of postmask boundaries. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 893-909.

Jordan, T.R. (1995). Perceiving exterior letters of words: Differential influences of letter-fragment and nonletter fragment masks. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 512-530.

Kemper, S., Crow, A., & Kemtes, K. (2004). Eye-fixation patterns of high and low-span young and older adults: Down the garden path and back. *Psychology and Aging, 19*, 157-170.

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*, 262-284.

Laubrock, J., Kliegl, R., & Engbert, R. (2006). SWIFT explorations of age differences in eye movements during reading. *Neuroscience and Biobehavioral Reviews, 30*, 872-884.

Leat, S.J., & Munger, R. (1994). A new application of band-pass fast Fourier transforms to the study of reading performance. In *Vision science and its applications* (Technical Digest Series, Vol. 2, pp. 250-253). Washington, DC: Optical Society of America.

Legge, G.E., Pelli, D.G., Rubin, G.S., & Schleske, M.M. (1985). Psychophysics of reading: I. Normal vision. *Vision Research*, *25*, 239-252.

Lovegrove, W.J., Bowling, A., Badcock, D., & Blackwood, M. (1980). Specific reading disability: Differences in contrast sensitivity as a function of spatial frequency. *Science*, *210*, 439-440.

Madden, D.J. (1988). Adult age differences in the effects of sentence context and stimulus degradation during visual word recognition. *Psychology and Aging*, *3*, 167-172.

Mansfield, J.S., Ahn, S.J., Legge, G.E., & Luebker, A. (1993). A new reading-acuity chart for normal and low vision. *Ophthalmic and Visual Optics / Noninvasive Assessment of the Visual System Technical Digest*, *3*, 232-235.

Martin, A., Cornelissen, P., Fowler, S., & Stein, J. (1993). Contrast sensitivity, ocular dominance and specific reading disability. *Clinical Vision Science*, *8*, 345-353.

McConkie, G.W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics*, *17*, 578-586.

McConkie, G.W., & Rayner, K. (1976). Asymmetry of the perceptual span in reading. *Bulletin of the Psychonomic Society*, *8*, 365-68

McGowan, V.A., Paterson, K.B., & Jordan, T.R. (2012). Age-related visual impairments and perceiving linguistic stimuli: The rarity of assessing the visual abilities of older participants in language research. *Experimental Aging Research*, in press.

Miellet, S., O'Donnell, P.J., & Sereno, S.C. (2009). Parafoveal magnification: Visual acuity does not modulate the perceptual span in reading. *Psychological Science*, *20*, 721-728.

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*, 1610-1622.

Owsley, C., Sekuler, R., & Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision*

Research, *23*, 689–699.

Patching, G.R., & Jordan, T.R. (2005a). Assessing the role of different spatial frequencies in word perception by good and poor readers. *Memory & Cognition*, *33*, 961-971.

Patching, G.R., & Jordan, T.R. (2005b). Spatial frequency sensitivity differences between adults of good and poor reading ability. *Investigative Ophthalmology & Visual Science*, 46, 2219-2224.

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

Pollatsek, A., & Rayner, K. (1982). Eye movement control in reading: The role of word boundaries. *Journal of Experimental Psychology: Human Perception and Performance*, *8*, 817-833.

Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology*, *41*, 211-236.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*, 372-422.

Rayner, K. (2009). The Thirty Fifth Sir Frederick Bartlett Lecture: Eye movements and attention during reading, scene perception, and visual search. *Quarterly Journal of Experimental Psychology*, *62*, 1457-1506.

Rayner, K., & Bertera, J. H. (1979). Reading without a fovea. *Science*, *206*, 468–469.

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

Rayner, K., Castelhano, M.S., & Yang, J. (2010). Preview benefit during eye fixations in reading for older and younger readers. *Psychology and Aging*, *25*, 714-718.

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

Rayner, K., Murphy, L. A., Henderson, J. M., & Pollatsek, A. (1989). Selective attentional dyslexia. *Cognitive Neuropsychology*, *6*, 357-378.

Rayner, K., Reichle, E.D., Stroud, M.J., Williams, C.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., Well, A.D., Pollatsek, A., & Bertera, J.H. (1982). The availability of useful information to the right of fixation in reading. *Perception & Psychophysics*, 31, 537-550.

Reichle, E.D., Liversedge, S.P., Rayner, K., & Pollatsek, A. (2009). Encoding multiple words simultaneously in reading is implausible. *Trends in Cognitive Sciences*, *13*, 115-119.

Riggs, L.A. (1965). Visual acuity. In C. H. Graham (Ed.), *Vision and visual perception* (pp. 321–349). New York: Wiley.

Risse, S., & Kliegl, R. (2011). Adult age differences in the perceptual span during reading. *Psychology and Aging*, *26*, 451-460.

Robson, J.G. (1966). Spatial and temporal contrast sensitivity functions of the visual system. *Journal of the Optical Society of America*, *56*, 141-14.

Stine-Morrow, E.A.L., Miller, L.M.S., Gagne, D.D., & Hertzog, C. (2008). Self-regulated reading in adulthood. *Psychology and Aging*, *23*, 131-153.

Underwood, N.R. & McConkie, G.W. (1985). Perceptual span for letter distinctions during reading. *Reading Research Quarterly*, *20*, 153-162.

FIGURES

Figure 1. Example of a sentence displayed normally and in each spatial frequency (for a 5-letter window of normal text). The appearance of the visual content shown in the figure is approximate due to restrictions in resolution and print medium.

Figure 2. Mean reading times for (a) Young Adult Readers and (b) Older Adult Readers in Experiment 1. Bars correspond to Standard Errors.

Figure 3. Mean reading times for (a) Young Adult Readers and (b) Older Adult Readers in Experiment 2. Bars correspond to Standard Errors.

Figure 1

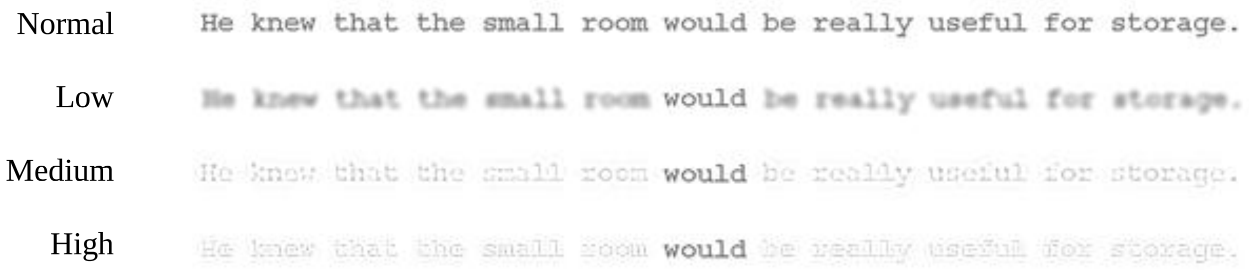

Normal
He knew that the small room would be really useful for storage.
Low
would
Medium
would
High
would

Figure 2

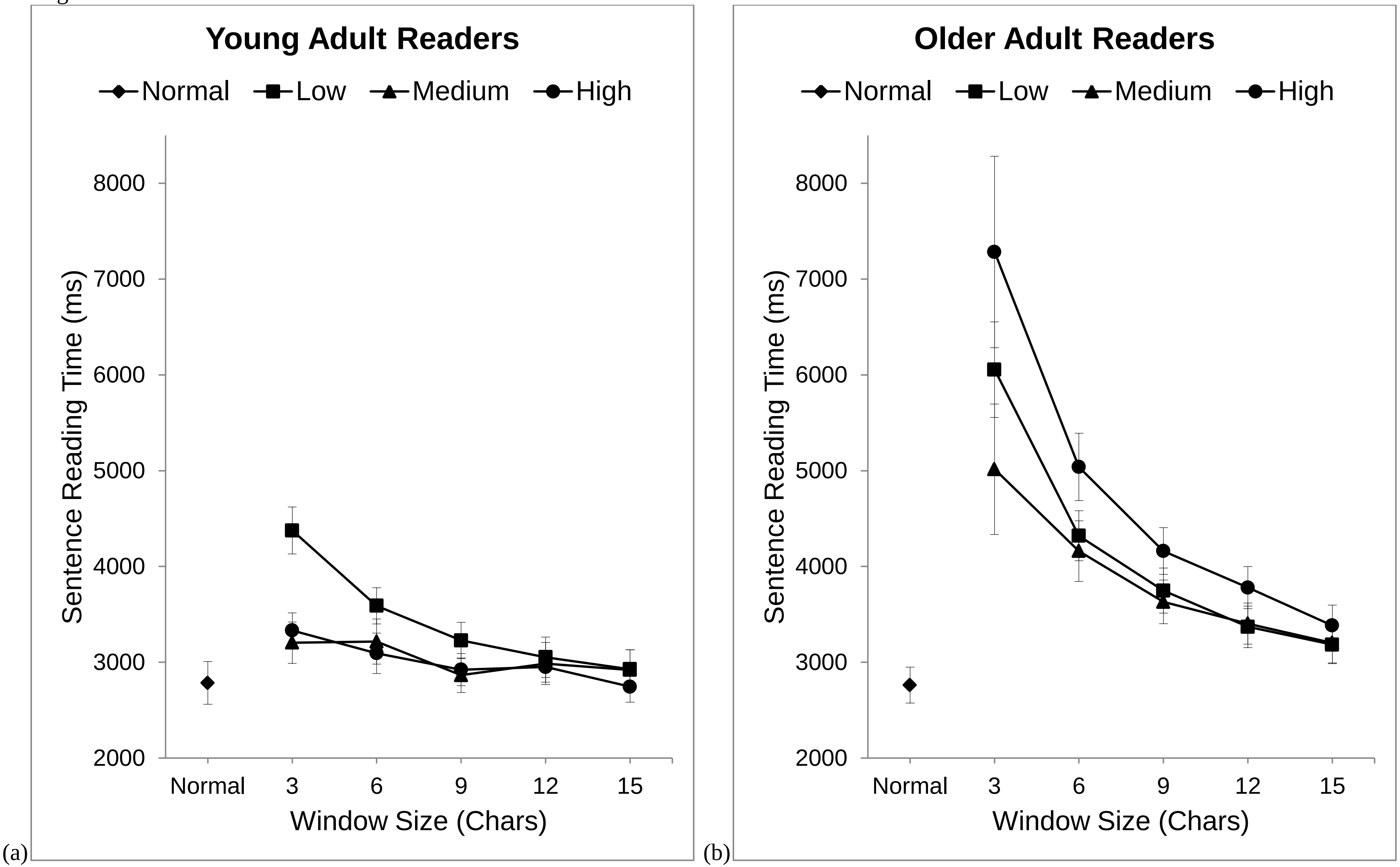
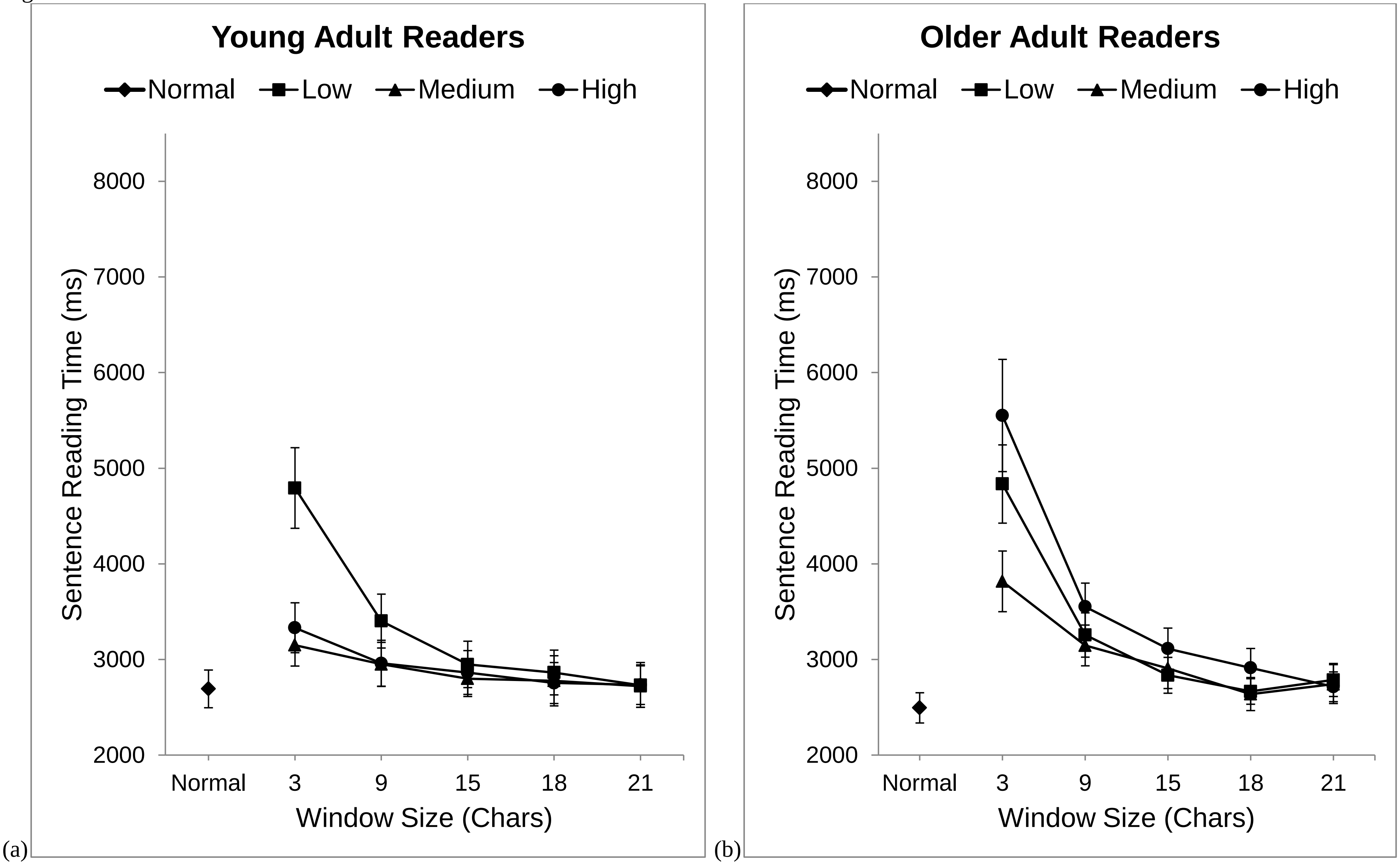

Young Adult Readers
Normal
Low
Medium
High
Sentence Reading Time (ms)
8000
7000
6000
5000
4000
3000
2000
Normal
3
6
9
12
15
Window Size (Chars)
(a)
Older Adult Readers
Normal
Low
Medium
High
Sentence Reading Time (ms)
8000
7000
6000
5000
4000
3000
2000
Normal
3
6
9
12
15
Window Size (Chars)
(b)

Figure 3



Young Adult Readers
Normal
Low
Medium
High
Sentence Reading Time (ms)
2000
3000
4000
5000
6000
7000
8000
Normal
3
9
15
18
21
Window Size (Chars)
(a)
Older Adult Readers
Normal
Low
Medium
High
Sentence Reading Time (ms)
2000
3000
4000
5000
6000
7000
8000
Normal
3
9
15
18
21
Window Size (Chars)
(b)

Table 1: Summary of Participant Characteristics

	Age (years)	Formal Education (years)	Reading Experience (hours / week)	High Contrast Distance Acuity	Low Contrast Distance Acuity	High Contrast Near Acuity	Low Contrast Near Acuity
Experiment 1							
Young Adults	*M* = 22 Range: 19-29	*M* = 17.2 Range: 15-20	*M* = 14.5 Range: 5-35	*M* = 20/17 Range: 20/13-20/26	*M* = 20/26 Range: 20/19-20/36	*M* = 20/17 Range: 20/13-20/21	*M* = 20/21 Range: 20/16-20/26
Older Adults	*M* = 69 Range: 65-75	*M* = 15.6 Range: 10-22	*M* = 15.0 Range: 3-40	*M* = 20/20 Range: 20/14-20/24	*M* = 20/30 Range: 20/24-20/40	*M* = 20/21 Range: 20/16-20/36	*M* = 20/32 Range: 20/21-20/42
Experiment 2							
Young Adults	*M* = 21 Range: 18-30	*M* = 15.9 Range: 11-19	*M* = 12.1 Range: 2-31	*M* = 20/17 Range: 20/13-20/25	*M* = 20/26 Range: 20/20-20/36	*M* = 20/19 Range: 20/11-20/28	*M* = 20/23 Range: 20/20-20/32
Older Adults	*M* = 69 Range: 65-77	*M* = 16.2 Range: 10-25	*M* = 16.4 Range: 2-40	*M* = 20/21 Range: 20/14-20/30	*M* = 20/33 Range: 20/24-20/46	*M* = 20/23 Range: 20/17-20/44	*M* = 20/31 Range: 20/21-20/46

Table 2: Eye Movement Measures of Young and Older Adults for Different Spatial Frequency Content and Window Conditions in Experiment 1.*

	Spatial Frequencies															
	Normal	Low					Medium					High				
		Window Size (chars)														
		3	6	9	12	15	3	6	9	12	15	3	6	9	12	15
Fixation Duration																
Young	212	270	247	232	226	222	239	231	224	224	221	238	231	225	226	222
	(7)	(10)	(10)	(8)	(8)	(7)	(7)	(7)	(7)	(7)	(7)	(7)	(7)	(7)	(8)	(8)
Older	231	305	278	263	255	250	283	268	262	253	248	319	283	266	255	247
	(7)	(11)	(10)	(10)	(11)	(9)	(12)	(11)	(10)	(10)	(10)	(13)	(11)	(10)	(10)	(11)
Number of Fixations																
Young	11.1	14.4	12.8	12.3	11.8	11.6	11.7	12.4	11.1	11.4	11.3	12.3	11.7	11.3	11.5	10.9
	(.9)	(.9)	(.7)	(.8)	(.7)	(.8)	(.8)	(.9)	(.7)	(.8)	(.8)	(.7)	(.8)	(.7)	(.7)	(.8)
Older	10.1	17.1	13.7	12.5	11.4	11.1	14.5	13.5	12.1	11.7	11.2	18.5	15.5	13.6	13.0	11.9
	(.6)	(1.2)	(.8)	(.7)	(.7)	(.7)	(.6)	(.9)	(.7)	(.7)	(.8)	(1.6)	(.9)	(.7)	(.7)	(.7)
Number of Regressions																
Young	2.5	3.1	2.7	2.8	2.7	2.6	2.3	2.7	2.3	2.5	2.7	2.4	2.3	2.1	2.4	2.1
	(.4)	(.4)	(.4)	(.4)	(.4)	(.4)	(.3)	(.3)	(.3)	(.3)	(.4)	(.3)	(.3)	(.3)	(.3)	(.3)
Older	2.9	4.9	3.5	3.2	2.7	2.6	3.7	3.5	2.8	2.8	2.8	4.1	3.2	2.6	2.7	2.4
	(.3)	(.6)	(.5)	(.3)	(.4)	(.4)	(.4)	(.4)	(.4)	(.4)	(.4)	(.5)	(.4)	(.3)	(.3)	(.3)
Progressive saccade length																
Young	7.6	6.0	6.7	7.0	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.0	7.0	7.0	7.6	6.0

	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)
Older	8.7	6.3	6.3	7.0	7.0	7.0	6.3	6.7	6.7	6.7	7.0	5.3	5.3	5.7	6.0	6.3
	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)

* Durations are reported in milliseconds, saccade lengths are reported in number of characters, and Standard Errors are provided in parentheses.

Table 3: Statistical Values for Analyses of Eye Movement Data for Experiment 1

	Source of Variance	df	F_1 value	η_p^2	df	F_2 value	η_p^2
Sentence Reading Time							
Low	Age group	1,30	3.43+	.11	1,159	125.85***	.44
	Window Size	5,150	82.61***	.73	5,795	108.18***	.41
	Age Group x Window Size	5,150	9.43***	.24	5,795	13.59***	.08
Medium	Age group	1,30	4.25*	.12	1,159	74.57***	.32
	Window Size	5,150	14.07***	.32	5,795	32.41***	.17
	Age Group x Window Size	5,150	6.39***	.18	5,795	14.63***	.08
High	Age group	1,30	15.19**	.34	1,159	295.49***	.65
	Window Size	5,150	23.16***	.44	5,795	74.57***	.32
	Age Group x Window Size	5,150	13.72***	.31	5,795	42.71***	.21
Fixation Duration							
Low	Age group	1,30	5.49*	.16	1,159	340.81***	.68
	Window Size	5,150	119.79***	.80	5,795	88.01***	.36
	Age Group x Window Size	5,150	1.58	.05	5,795	.94	.01
Medium	Age group	1,30	7.52*	.20	1,159	415.19***	.72
	Window Size	5,150	42.54***	.59	5,795	35.06***	.18
	Age Group x Window Size	5,150	4.98***	.14	5,795	2.97***	.02
High	Age group	1,30	11.66**	.28	1,159	687.30***	.81
	Window Size	5,150	80.65***	.73	5,795	67.00***	.30
	Age Group x Window Size	5,150	28.41***	.49	5,795	19.72***	.11
Number of Fixations							
Low	Age group	1,30	.10	.00	1,159	2.35	.02
	Window Size	5,150	46.05***	.61	5,795	46.06***	.23
	Age Group x	5,150	5.94***	.17	5,795	6.60***	.04

	Window Size						
Medium	Age group	1,30	.47	.02	1,159	2.11	.02
	Window Size	5,150	15.75***	.34	5,795	19.80***	.11
	Age Group x Window Size	5,150	7.82***	.21	5,795	12.00***	.07
High	Age group	1,30	4.78*	.14	1,159	170.43***	.52
	Window Size	5,150	28.48***	.49	5,795	42.51***	.21
	Age Group x Window Size	5,150	15.62***	.34	5,795	23.21***	.13
Number of Regressions							
Low	Age group	1,30	1.32	.04	1,159	1.23	.01
	Window Size	5,150	14.65***	.33	5,795	16.34***	.09
	Age Group x Window Size	5,150	5.98***	.17	5,795	6.42***	.04
Medium	Age group	1,30	1.42	.05	1,159	1.68	.01
	Window Size	5,150	4.15**	.12	5,795	2.91***	.02
	Age Group x Window Size	5,150	4.62**	.13	5,795	3.27***	.02
High	Age group	1,30	2.64	.08	1,159	2.16	.01
	Window Size	5,150	8.44***	.22	5,795	10.47***	.06
	Age Group x Window Size	5,150	5.07***	.14	5,795	3.95***	.03
Progressive Saccade Length							
Low	Age group	1,30	.13	.00	1,159	.09	.00
	Window Size	5,150	38.54***	.56	5,795	25.84***	.14
	Age Group x Window Size	5,150	6.64***	.18	5,795	5.41***	.03
Medium	Age group	1,30	.12	.00	1,159	2.91	.02
	Window Size	5,150	20.95***	.41	5,795	19.54***	.11
	Age Group x Window Size	5,150	9.18***	.23	5,795	10.35***	.06
High	Age group	1,30	1.04	.03	1,159	2.75	.02
	Window Size	5,150	47.15***	.61	5,795	61.41***	.28
	Age Group x	5,150	16.01***	.35	5,795	697.12***	.37

Window Size

---

* $p < .05$.
** $p < .01$.
*** $p < .001$.
+ $.1 > p > .05$.

Table 4: Eye Movement Measures of Young and Older Adults for Different Spatial Frequency Content and Window Conditions in Experiment 2.*

	Spatial Frequencies															
	Normal	Low					Medium					High				
		Window Size (chars)														
		3	9	15	18	21	3	9	15	18	21	3	9	15	18	21
Fixation Duration																
Young	229	291	246	238	235	233	256	243	238	237	232	256	238	237	235	234
	(6)	(6)	(7)	(6)	(7)	(7)	(6)	(8)	(6)	(7)	(6)	(7)	(6)	(7)	(7)	(7)
Older	233	294	263	243	238	238	272	255	247	240	238	309	262	245	239	239
	(8)	(12)	(10)	(10)	(9)	(9)	(12)	(11)	(10)	(11)	(9)	(15)	(12)	(10)	(12)	(10)
Number of Fixations																
Young	9.9	14.4	12.0	10.7	10.4	10.0	10.6	10.5	10.1	10.2	10.0	11.3	10.8	10.4	10.1	10.1
	(.6)	(.9)	(.9)	(.9)	(.7)	(.6)	(.6)	(.7)	(.6)	(.9)	(.7)	(.8)	(.8)	(.8)	(.7)	(.8)
Older	9.3	14.9	11.6	10.2	10.0	10.4	12.5	11.0	10.4	9.8	10.2	15.8	12.0	11.1	10.6	9.9
	(.6)	(1.0)	(.7)	(.5)	(.5)	(.6)	(.8)	(.6)	(.6)	(.5)	(.6)	(1.2)	(.6)	(.6)	(.5)	(.4)
Number of Regressions																
Young	2.5	3.0	2.5	2.5	2.5	2.5	2.1	2.3	2.2	2.5	2.4	2.2	2.3	2.2	2.3	2.3
	(.3)	(.4)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.2)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)
Older	2.5	4.2	2.8	2.5	2.5	2.6	3.4	2.5	2.4	2.2	2.5	3.9	2.4	2.3	2.1	2.0
	(.3)	(.5)	(.3)	(.3)	(.2)	(.3)	(.3)	(.3)	(.2)	(.2)	(.3)	(.4)	(.2)	(.2)	(.2)	(.2)
Progressive Saccade Length																
Young	7.3	6.0	6.3	6.0	7.3	7.7	7.3	7.0	7.3	7.7	7.7	6.7	6.7	7.0	7.3	6.0

	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)
Older	9.0	7.3	7.7	8.0	8.3	8.3	7.7	7.3	7.7	7.7	8.0	6.3	6.7	6.0	6.0	7.3
	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)	(.3)

* Durations are reported in milliseconds, saccade lengths are reported in number of characters, and Standard Errors are provided in parentheses.

Table 5: Statistical Values for Analyses of Eye Movement Data for Experiment 2

	Source of Variance	df	F_1 value	η_p^2	df	F_2 value	η_p^2
Sentence Reading Time							
Low	Age group	1,30	.05	.00	1,159	1.25	.01
	Window Size	5,150	74.84***	.71	5,795	109.07***	.41
	Age Group x Window Size	5,150	.62	.02	5,795	1.13	.04
Medium	Age group	1,30	.76	.03	1,159	1.24	.04
	Window Size	5,150	35.23***	.54	5,795	26.02***	.14
	Age Group x Window Size	5,150	7.91***	.21	5,795	9.64***	.06
High	Age group	1,30	4.69***	.55	1,159	194.03***	.55
	Window Size	5,150	39.17***	.57	5,795	81.22***	.34
	Age Group x Window Size	5,150	18.47***	.38	5,795	55.93***	.26
Fixation Duration							
Low	Age group	1,30	.18	.01	1,159	1.78	.01
	Window Size	5,150	151.26***	.83	5,795	70.21***	.31
	Age Group x Window Size	5,150	1.63	.05	5,795	1.41	.01
Medium	Age group	1,30	.45	.02	1,159	1.71	.01
	Window Size	5,150	33.34***	.53	5,795	17.10***	.10
	Age Group x Window Size	5,150	2.31*	.07	5,795	2.11+	.01
High	Age group	1,30	1.53	.05	1,159	1.39	.01
	Window Size	5,150	54.38***	.64	5,795	37.75***	.19
	Age Group x Window Size	5,150	17.27***	.37	5,795	23.98***	.13
Number of Fixations							
Low	Age group	1,30	.01	.00	1,159	2.53	.02
	Window Size	5,150	51.16***	.63	5,795	87.68	.36
	Age Group x	5,150	.65	.02	5,795	1.31	.01

	Window Size						
Medium	Age group	1,30	.40	.01	1,159	.38	.00
	Window Size	5,150	19.41***	.39	5,795	39.33***	.20
	Age Group x Window Size	5,150	6.24***	.17	5,795	34.15***	.18
High	Age group	1,30	2.99+	.09	1,159	37.33***	.19
	Window Size	5,150	36.09***	.55	5,795	84.94***	.35
	Age Group x Window Size	5,150	16.18***	.35	5,795	55.51***	.26
Number of Regressions							
Low	Age group	1,30	1.75	.06	1,159	1.95	.06
	Window Size	5,150	12.01***	.29	5,795	14.97***	.08
	Age Group x Window Size	5,150	4.86***	.14	5,795	6.64***	.04
Medium	Age group	1,30	1.59	.05	1,159	2.19	.01
	Window Size	5,150	3.09***	.09	5,795	2.77*	.02
	Age Group x Window Size	5,150	6.83***	.19	5,795	6.99***	.04
High	Age group	1,30	1.81	.06	1,159	2.16	.01
	Window Size	5,150	10.76***	.26	5,795	13.61***	.08
	Age Group x Window Size	5,150	15.06***	.33	5,795	19.21***	.11
Progressive Saccade Length							
Low	Age group	1,30	5.25***	.35	1,159	152.07***	.49
	Window Size	5,150	48.07***	.62	5,795	46.63***	.23
	Age Group x Window Size	5,150	3.51***	.11	5,795	3.04***	.09
Medium	Age group	1,30	1.53	.05	1,159	2.85	.02
	Window Size	5,150	24.30***	.45	5,795	20.50***	.11
	Age Group x Window Size	5,150	9.54***	.24	5,795	5.03***	.02
High	Age group	1,30	.07	.00	1,159	2.83+	.02
	Window Size	5,150	53.82***	.64	5,795	56.48***	.26
	Age Group x	5,150	15.87***	.35	5,795	16.27***	.03

Window Size

* $p < .05$.
** $p < .01$.
*** $p < .001$.
+ $.1 > p > .05$.